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DEVELOPMENT OF A SCANNING ELECTRON MIRROR MICROSCOPE

By R. E. Ogilvie, S. H. Moll and M. A. Schippert

March 1968

Interim Scientific Report

Prepared under Contract No. NAS 12-524 by

ADVANCED METALS RESEARCH CORPORATION
Burlington, Massachusetts

Failure Mechanisms Branch
Qualifications and Standards Laboratory
Electronic Components Research
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DEVELOPMENT OF A SCANNING ELECTRON MIRROR MICROSCOPE

By R. E. Ogilvie, S. H. Moll and M. A. Schippert

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SUMMARY

A research program was carried out in order to investigate the fundamental feasibility of a Scanning Electron Mirror Microscope. This instrument, to be applied to the study of microelectronic devices uses a finely focused beam of electrons to scan the device surface. The specimen is maintained at an electrostatic potential equivalent to that of the electron gun. Electrons incident on the specimen lose their kinetic energy upon reaching the sample surface and are then reflected and reaccelerated in the opposite direction. Local variations in the potential fields at the sample surface produced by voltage junctions, differences in contact potentials, surface conductivity, topography or even magnetic fields, strongly influence the direction of the reflected electrons. The variations in the direction and intensity of the reflected electron beam seen by a detector modulate the brightness of a cathode ray tube raster, thus producing images of the electrical or magnetic characteristics of the sample surface.

The design of an appropriate electron mirror was optimized by use of analog field plotting experiments. A simple, prototype Scanning Electron Mirror Microscope was then constructed which incorporated two electron lenses, a scanning display system and a simplified version of an electron mirror sample chamber.

Experiments designed to form the basis for the development of

a final instrument were also carried out. These included studies of the electron beam trajectories as a function of tilt of the electron mirror axis and the application of varying surface potential gradients to the sample. The feasibility of scanning the electron beam within the electron mirror was proved. Variations in contrast and resolution of the scanning display image were investigated as a function of the size, shape and position of the electron detector and the strength of the axial voltage field gradient in the mirror.

The results of these experiments formed the basis for the design development of a Scanning Electron Mirror Microscope capable of area resolution of 1000A° and a minimum electric field gradient detectability of 0.3 volts/cm.

INTRODUCTION

In recent years the recognition of the possibility of focusing electron beams with magnetic or electrostatic lens systems has resulted in the development of a family of electron optical instruments which have been used with great success in the study of materials. A great deal of interest has been centered about the application of these instruments to the study and evaluation of semiconductor devices.

Up to the present time, perhaps the most successful instrument has been the scanning electron microscope. In this instrument a finely focused beam of high energy electrons impinges on the surface of the specimen and is scanned rapidly back and forth in the form of a raster which covers the chosen area of the surface. A cathode ray tube is synchronized with the movement of the electron beam to produce an image of the scanned area. The interaction of the electron beam with the electronic characteristic of the device at each point is continuously monitored by detectors which modulate the brightness of the cathode ray beam, forming an image of the specimen in areas of light and dark. Various characteristics of the device can be represented and its performance evaluated.

It has been observed, however, that in many semiconductor materials, the impact of the high energy electrons may produce a significant deterioration and a change in the performance of the device. In addition, the electron beam will induce large circuit currents in the device which is not a normal operating condition. Consequently, the scanning electron microscope must be considered, in a sense at least, a destructive test of the device in question. The development of a truly non-destructive method of investigation is of great urgency.

To meet this need, a scanning electron mirror microscope is being developed which is based on a combination of principles which represent an entirely new approach to the problem, an approach which is not within the scope of any existing or proposed instruments in the field. In this instrument, again, a finely focused beam of electrons is directed at the specimen and scanned over an area in the form of a raster. The specimen surface, however, is maintained at a controlled potential such that as the electrons approach it, they are decelerated, stopped very close to the surface and then reaccelerated in the opposite direction, the specimen surface thus acting as an electron mirror. Precise control of the specimen potential permits the reflection point to be brought as close to the surface as desired but the electrons do not touch the surface so that there is no deterioration of the semiconductor material due to electron impact.

The direction in which an electron is reflected in this process is very sensitive to the electric field gradients existing very close to the specimen surface, these gradients being the result of the currents flowing in the semiconductor device in its normal (or abnormal) operation. A multiplicity of electron detectors determine the angular distribution of the reflected electrons and these detectors are coupled to the synchronized oscilloscope in such a way that an image or map of the surface potential gradient distribution is displayed. Sensitivity to potential gradients of different magnitudes may be varied over wide limits, the spacial resolution may be adjusted and various methods of image display may be employed to suit particular purposes.

The fact that the method is nondestructive means that the test itself does not impair the specimen in any way and thus appears ideally suited for the inspection, testing and evaluation of integrated circuit devices where extremely high reliability is the most important criterion.

The objective of the research program to be described was to develop and design an advanced scanning electron mirror microscope which would have the capability of examining integrated circuits under operating conditions for determination of potential failure mechanisms. It is essential that the examination be harmless to the devices such that the technique could be used as a screening method.

Item 1 - Develop a scanning electron mirror microscope for non-destructive inspection of integrated circuits. The minimum resolution shall be 1000A°., the minimum sensitivity shall be 10 millivolts, and the maximum ion current shall be 10^{-10} ampere.

Item 2 - Prepare detailed design drawings suitable for construction of the scanning electron mirror microscope developed under Item 1.

This report describes the conduct and results of the experimental program and also discusses the detailed design of a proposed high quality Scanning Electron Mirror Microscope which evolved.

EXPERIMENTAL PROGRAM

The experimental program followed during the past year was essentially divided into three separate areas. The first area of interest consisted of Analog Field Plotting Experiments which were carried out in order to test the design concepts of the electron mirror chamber. After this, a prototype Scanning Electron Mirror Microscope was constructed according to the results of the analytical study. Finally, significant experimentation was carried out in order to test the performance of the electron mirror, scanning system, detectors, etc.

Principle of the Electron Mirror

In a Scanning Electron Mirror Microscope, the "image" representing potential gradients on a specimen surface results from the reflection scattering of a decelerated electron beam at a point just above, or at, the specimen surface. The electron beam is reflected from each point on the surface at an angle which depends upon the potential gradient present at that point. If the cathode mirror (specimen) lies perpendicular to the electron beam and no potential gradient is present, the electrons will be accelerated directly back towards the gun. It would be extremely valuable to be able to intercept the "normally" reflected electron beam. However, if the beam retraces its original path then a detector placed in its path also intercepts the incident beam. To eliminate this problem, the cathode plate may be tilted by a small angle (2 to 5°). The electrons are then essentially reflected as at a tilted light optical mirror, with the angle of incidence equal to the angle of reflection. In actuality, the electron beam follows a parabolic path with its vertex at the specimen surface. This trajectory is useful in that normally deflected electrons may be examined as well as electrons scattered by potential gradients.

This mirror concept was investigated. The aim of the mirror design program was to develop a tilted mirror configuration with the following design criteria.

a. Minimum protrusion of the mirror electric field through any aperture opening to prevent a lens action operating on the electron beam.

b. A variable but small axial field gradient near the sample surface for maximum potential gradient sensitivity.

c. An ideal cathode tilt angle to produce a sharply vertexed parabola with zero potential gradient along the sample surface.

d. Allow for undistorted raster scanning of the electron beam, at least in one direction, within a uniform field at the aperture opening.

Analog Field Plotting

Sectional scale drawings of variously shaped apertures, mirror configurations, etc., were analyzed to determine the shape of equipotential lines and the consequent electron trajectory paths.

An Electrostatic Analog Field Plotter was used to investigate these various designs. It was found that a multiple grid system, wherein the individual grids are biased with respect to ground at increasingly negative potentials as the cathode mirror is approached, yielded minimum aperture distortion and produced an excellent, uniform field between the last grid and the cathode mirror. A drawing of the proposed mirror is shown in Figure 1 for a gun potential slightly more positive than -20,000 volts.

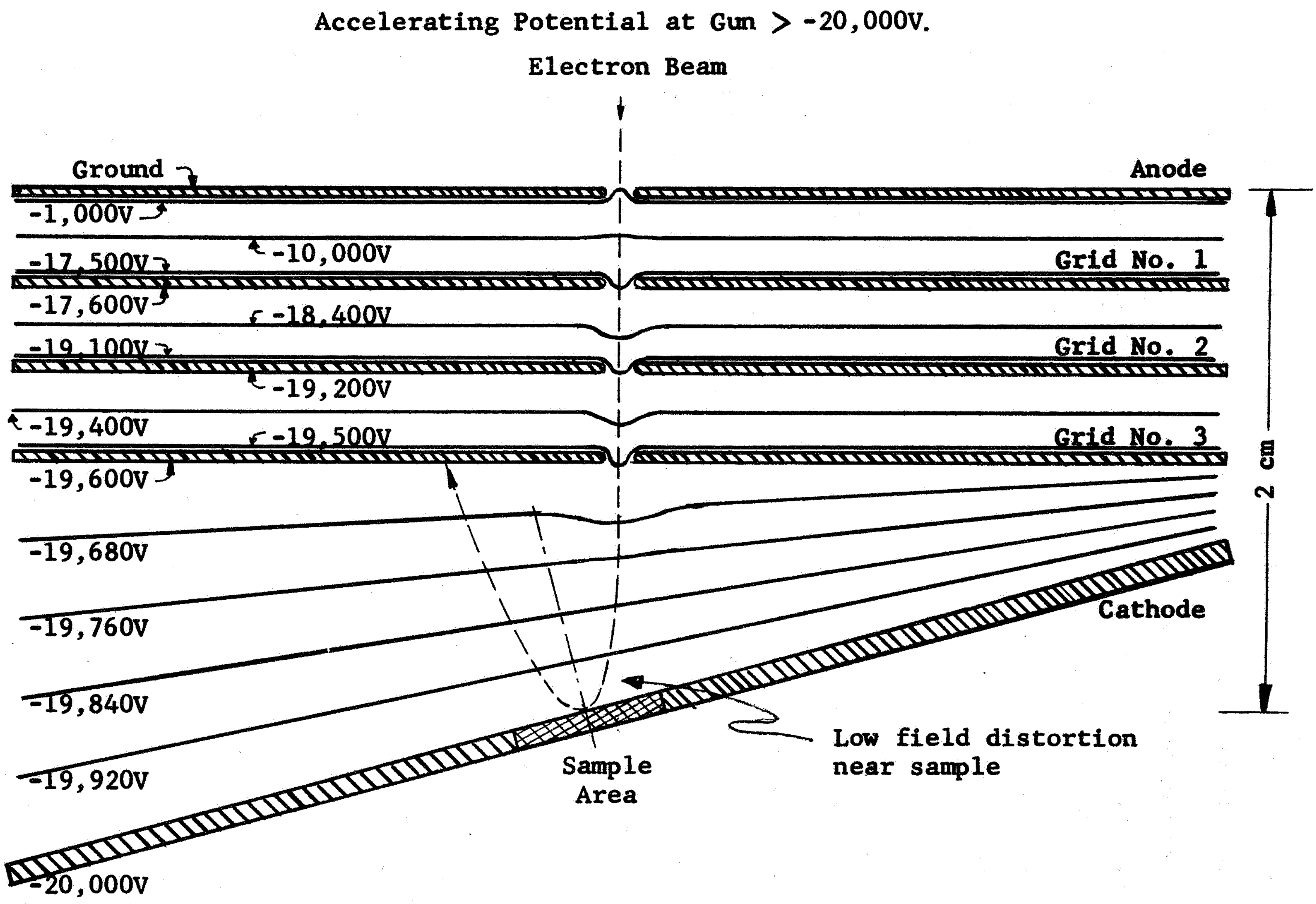


Figure 1 - Electron Path Through Multiple Grid Mirror with Tilted Cathode Plate

The small axial electric field gradient required near the sample surface is easily established by biasing the last grid at a voltage lying between 2 and 200 volts positive with respect to the cathode (sample). A simple mirror could be constructed without the biasing grids, but the potential gradient sensitivity would not be variable. Electron trajectories within the electron mirror were graphically determined by normal methods and found to conform closely to electron trajectories predicted by an analytical approach discussed below.

The analog field plotting experiments indicate that all apertures in the electron mirror should be elongated holes for minimum spot size aberration. These would provide uniform electric fields along a 2 mm line. The electron beam may be scanned in one direction along this line. Raster scanning in the other direction should be provided by a mechanical motion of the mirror electrode. Later experiments indicated that mechanical rastering will probably not be required, however.

Analytical Study of the Electron Mirror

The program carried out with the analog field plotter resulted in an electron mirror concept which appears to satisfy all of the design objectives. The electron mirror chamber shown in Figure 1 exhibits negligible aperture effects, yields a smooth, parabolic electron trajectory and allows for the strategic placement of electron detectors.

It is necessary that the entire electron path be predictable, as the parameters of the mirror such as tilt angle and grid bias voltage are changed. This is necessary in order that apertures in the grids and electron detectors may be properly placed to allow for the electron trjaectories developed. It would be possible to plot the electron trajectories by varying, step by step, the mirror parameters, replotting the equipotential lines with the analog field plotter and then graphically constructing the new electron trajectory. Since this procedure would be extremely tedious it was decided to develop an analytical approach to the problem to be able to predict the electron paths.

Figure 2 is a schematic drawing of the electron mirror developed by use of the analog field plotter. The parabolic electron trajectory graphically constructed for this mirror condition is also shown. Various potential points and dimensions of interest are given on the drawing.

Let: $$V_o = V_{gun} - V_P = V_G - V_P \quad \text{(electron potential)} \qquad (1)$$

$$V' = \frac{V_{cathode} - V_P}{Y_o} = \frac{V_C - V_P}{Y_o} \quad \text{(electron potential gradient)} \qquad (2)$$

$$\theta = 90^\circ - \alpha$$

It can be shown that:

$$Y = \frac{-V' X^2}{4V_o \cos^2 \theta} + \tan \theta \qquad (3)$$

and $$X_o = 2 \sin 2\theta \frac{V_o}{V'} \qquad (4)$$

$$Y = \sin^2\theta \frac{V_o}{V'}$$

The absolute potential or potential differences are not important in determining electron trajectory. The trajectory would

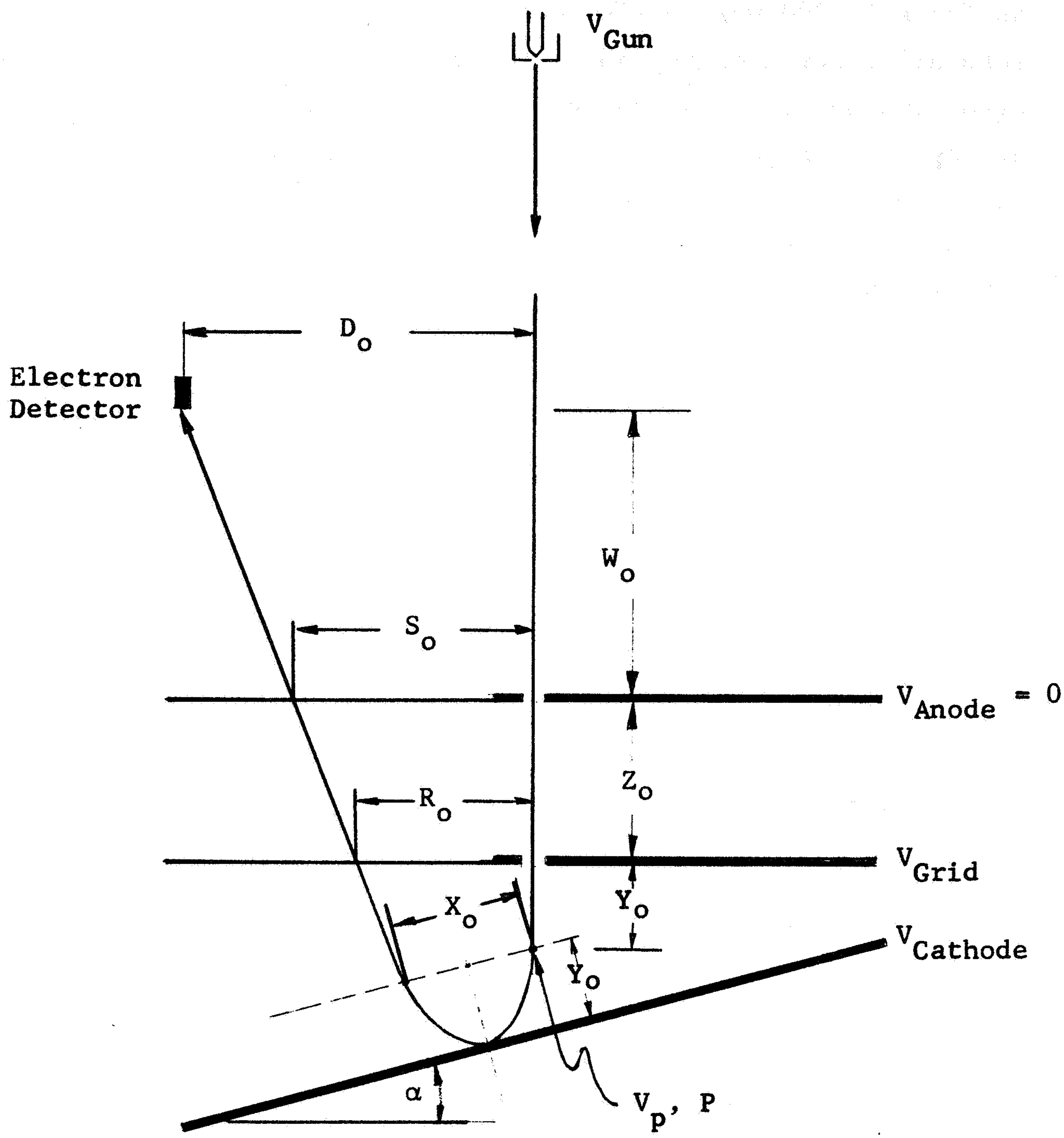


Figure 2 - Analytical Model and Convention
Simplified Prototype Electron Mirror

be the same for a 1 volt difference between mirror and ground as for a 10,000 volt difference, provided that the electrons lose all kinetic energy just at the mirror surface. Based on the equations above it is possible to derive the ratio between the voltage on the gun and that required on the cathode which will just turn the electrons around at the mirror. This ratio is simply a function of the tilt angle and the voltage produced at point P by the bias grid.

As an example, if the last grid is allowed to assume a field potential which results simply from its geometrical position lying between the ground plate and the cathode, and point P is 3/4 of the distance from the ground plate to the mirror plate, then:

$$\frac{V_C}{V_G} = \frac{\sin^2\theta}{4} + 3/4 \qquad (5)$$

This would represent a minimum value of this ratio and, if the electron potential at point P (V_P) is 99% of the cathode potential, then:

$$\frac{V_C}{V_G} = \frac{\sin^2\theta}{100} + 0.99 \qquad (6)$$

Using the formulas above and simple trigonometry it is possible to derive the following:

1. Maximum difference between V_G and V_C for various tilt angles. This corresponds to minimum V_C/V_G (equation 5) for which no bias would be applied within the mirror.

2. The position of the reflected electron beam at the final grid, anode (ground plate) and at the detector level as a function of tilt angle and the dimensions and voltages of the mirror.

These electron trajectory parameters have been calculated as a function of tilt angle for maximum potential difference between the gun and the cathode for:

$$W_o = 2 \text{ cm}, \; Z_o = 1 \text{ cm}, \; Y_o = 0.5 \text{ cm}$$

The values calculated are given in Table I. These values agree with those determined graphically within $\pm 10\%$ which is more than sufficient for design purposes.

With these formulas it should be possible to predict the electron trajectories which will be observed with both the prototype and final mirror design.

Table I

Calculated Electron Trajectory

Tilt Angle α	$\frac{V_G - V_C}{V_G}$ (100) max.	X_o	R_o	S_o	D_o (cm)
0	0	0	0	0	0
5	0.2	0.175	0.263	0.439	0.791
10	0.8	0.352	0.533	0.897	1.625
15	1.7	0.536	0.822	1.399	2.553
20	2.9	0.728	1.139	1.978	3.656
25	4.5	0.935	1.498	2.690	5.074
30	6.2	1.156	1.910	3.642	7.106
35	8.2	1.400	2.410	5.157	10.651
40	10.3	1.678	3.029	8.700	20.042
45	12.5	2.000	3.835	∞	∞

Conditions: V_C/V_G minimum, $W_o = 2$ cm, $Z_o = 1$ cm, $Y_o = 0.5$ cm

PROTOTYPE SCANNING ELECTRON MIRROR MICROSCOPE

The development of this instrument would not have been complete without some prototype testing on a suitable electron optical bench. Therefore, much of the effort during this program was devoted to the construction and assembly of a double lens electron optical column and its associated vacuum system and power supplies. The electron optical configuration of the column allows a demagnification of the hot filament electron source by a factor of at least 25 times. This will yield a focused electron beam, near the electron mirror, which is less than 10 microns in diameter.

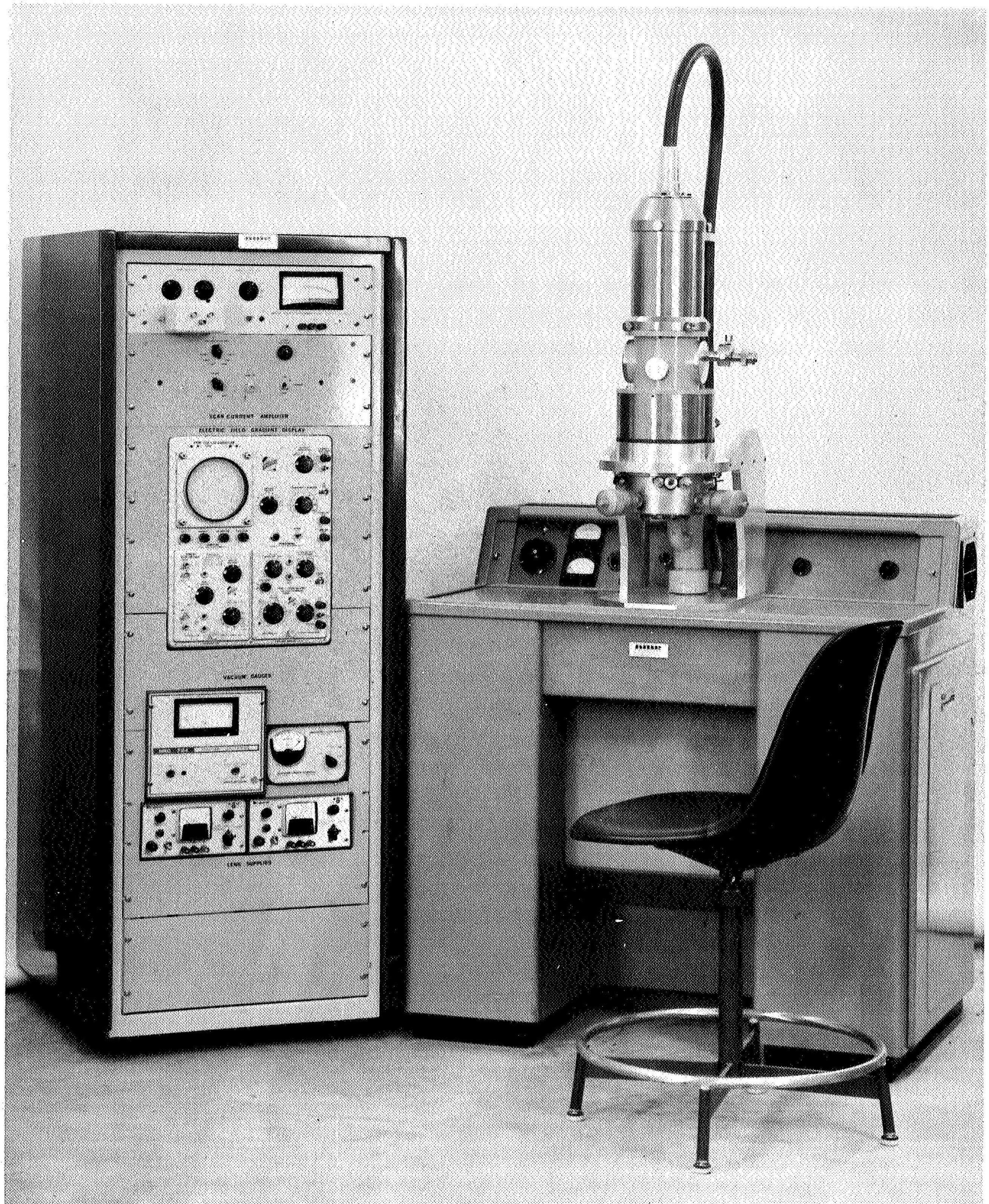
A probe spot reducing aperture 100μ in diameter, which is mounted to an x-y-z drive, was placed between the condenser and probe forming lens. The incident electron beam is reduced from 10μ in diameter to approximately 2 microns in diameter when the condenser lens is heavily excited. In the final instrument a third lens will be required to achieve beam spot sizes of 500 to 1000A°. A beam size of 10μ was small enough for all preliminary experimentation.

Electromagnetic alignment coils positioned directly below the electron gun and lateral adjustment screws on both the gun and the condenser lens facilitate the alignment of the column.

The electron optical column (Figure 3) is similar to that of an electron microprobe or scanning electron microscope except that the working distance of the final lens is longer. A focused beam must be produced on the bottom plate (cathode) of the electron mirror which is spaced from three to five cm from the principal plane of the final lens. An easily removable specimen chamber is attached to the lower part of the column. It contains

Figure 3

Electron Optical Column
Prototype Scanning Electron Mirror Microscope


ELECTRIC FIELD GRADIENT DISPLAY
VACUUM GAUGES
LENS SUPPLIES

the electron mirror and an electron detector for intercepting the reflected electrons.

The vacuum system employed is capable of producing operating pressures as low as 10^{-6} torr. It consists of a mechanical pump, a 2" oil diffusion pump, three high vacuum valves, two thermocouple gauges and one cold cathode high vacuum gauge. All valves are hand operated in this prototype model. An extended foreline serves as a limited buffer tank to back up the isolated oil diffusion pump when the column is prevacuated by the mechanical pump.

The lens power is supplied by highly regulated solid state current supplies. The lens currents are adjustable over a wide range to provide a variable focal length for the lenses.

The high voltage power supply (oil immersed) is variable from 0 to -30 KV with currents available to 200 microamperes. It supplies high voltage to the electron gun, power to the hot filament electron source, and variable voltages to the electron mirror cathode and the grids.

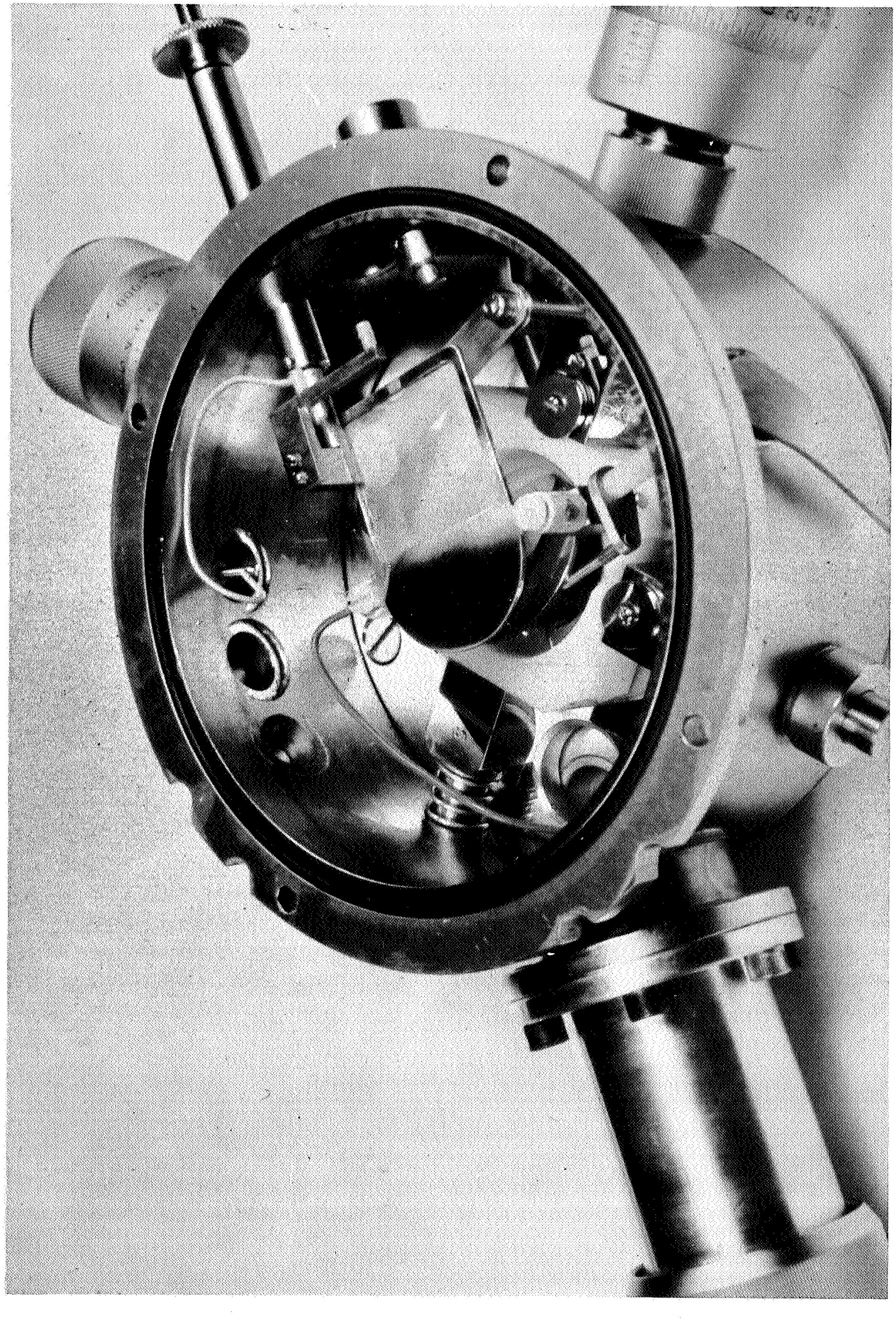
The potential variation on the mirror cathode and the grids is established by adjustable voltage dividers both in the power supply tank and also in the electron mirror housing (specimen chamber). The adjustments are readily made to meet any combination of potential differences required.

Electron Mirror Prototype

A prototype, simplified, electron mirror was built for a number of purposes, one of which was to study the electron reflection parabolas developed by variations in the mirror cathode tilt angles (Figure 4).

Figure 4

Prototype Electron Mirror and
Detection System



This model, based on the results of the Analog Field Plotting Experiments, consists of the anode and cathode plates only. These could be driven synchronously by an X-Y stage drive for alignment with the electron beam. The cathode plate operating at a potential close to that of the gun, could be tilted, by a mechanical feedthrough control, to any angle from 0° up to 30 degrees. A very fine wire mesh (75% transmission, 100 mesh) was originally installed to make up that part of the anode plate (ground) which allows the reflected and reaccelerated electron beam to pass through. The electron beam was then intercepted by an electron detector which lies above the anode. The wire mesh helps to maintain an even field distribution between the cathode and the anode. The electron detector, consisting of a single, fine metal wire, metal plate, or solid state device, can be traversed so as to intercept the reflected electron beam over the entire range of cathode tilt angles. The high voltage feedthrough cable entering the specimen chamber supplies the D.C. potential to the cathode plate during mirror operation. To facilitate the alignment of the column, the cable end normally connected to the high voltage supply may be connected to a high impedance voltmeter (virtual ground). By observing the absorbed electron current the column may be mechanically aligned. A zinc sulfide coated screen may also be positioned directly above the cathode plate to allow direct observation of the focused electron beam through a small lead glass window in the specimen chamber.

Scanning Display System

The scanning coils, for producing line and raster scans along two axes, are based on the Helmholtz coil principle and consist of two pairs of four coils. A common coil current deflects the electron beam entering the upper coil pair by an angle of θ, and the lower coil pair deflects the electron beam back again by an angle of 2θ. This results in a sweep-mode in which the electron beam incident on the mirror always passes through the same point at the principal plane of the final lens. Preliminary experimental studies indicated that the scanning coils could be situated above the final lens, rather than below, in contrast to an original projected design which allowed deflections parallel to the electron optical axis. This permits a shorter working distance between the final lens and the mirror and less mutual field interference. All studies were carried out with the coils above the final lens.

The scanning coils receive their drive current via a solid state current amplifier, which converts the 150 volt deflection sawtooth from the display oscilloscope to coil currents between 3.7 and 300 ma. The consequent scanning range extends over lengths variable from 33 microns to 2.5 mm which is equivalent to magnifications of about 40X to 3,000X if images are presented on the display face of a 10 cm x 10 cm cathode ray tube. A video preamplifier with a gain-bandwidth product of 1 MHZ is used with the scanning display.

EXPERIMENTATION WITH THE PROTOTYPE SCANNING ELECTRON MIRROR MICROSCOPE

Tilting the Electron Mirror

The varying trajectory of reflected electrons as a function of mirror plate tilt angle was studied experimentally. The mirror plate potential was varied as a function of the tilt angle to allow the electron beam to be reflected precisely at the surface of the mirror plate.

The precise mirror plate potentials required were attained by first allowing the electron beam to strike the mirror plate with a slight excess energy. Secondary electrons are produced and these are accelerated towards the anode. These electrons were intercepted with the movable detector. It is interesting to note that the secondary electrons appear in a diffuse beam close to the incident electron beam. The mirror potential was then reduced (voltage more negative) until the secondary electron current became zero.

A comparison between the predicted electron path and the measured electron path is shown in Table II. The horizontal displacement between the incident electron beam and the reflected electron beam at the detector position is given. The excellent agreement between the experimental and calculated electron beam displacements is also evident in Figure 5.

Experiments were also carried out with a constant voltage on the electron mirror equal to that on the gun. As a result, as the mirror tilt angle was increased, the electron beam was reflected at a distance from the mirror which increased with tilt angle. Under these conditions a loss of image resolution might be

Table II

Comparison of Calculated and Experimental Electron Trajectory Parameters

Tilt Angle α	$\left(\frac{V_G - V_C}{V_G}\right)_{max.}$ (100)	Detector Distance from Column Center (D_o - cm) Calculated	Experimental
0	0	0	-
5.0	0.2	0.791	0.787
7.5	0.4	1.220	1.245
10.0	0.8	1.625	1.525
12.5	1.2	2.080	2.080
15.0	1.7	2.553	2.560
17.5	2.2	3.080	3.100
20.0	2.9	3.656	3.780
22.5	3.6	4.320	4.190
25.0	4.5	5.074	-

V_C/V_G adjusted for electron reflection at mirror plate surface.

$W_o = 2$ cm, $Z_o = 1$ cm, $Y_o = 0.5$ cm

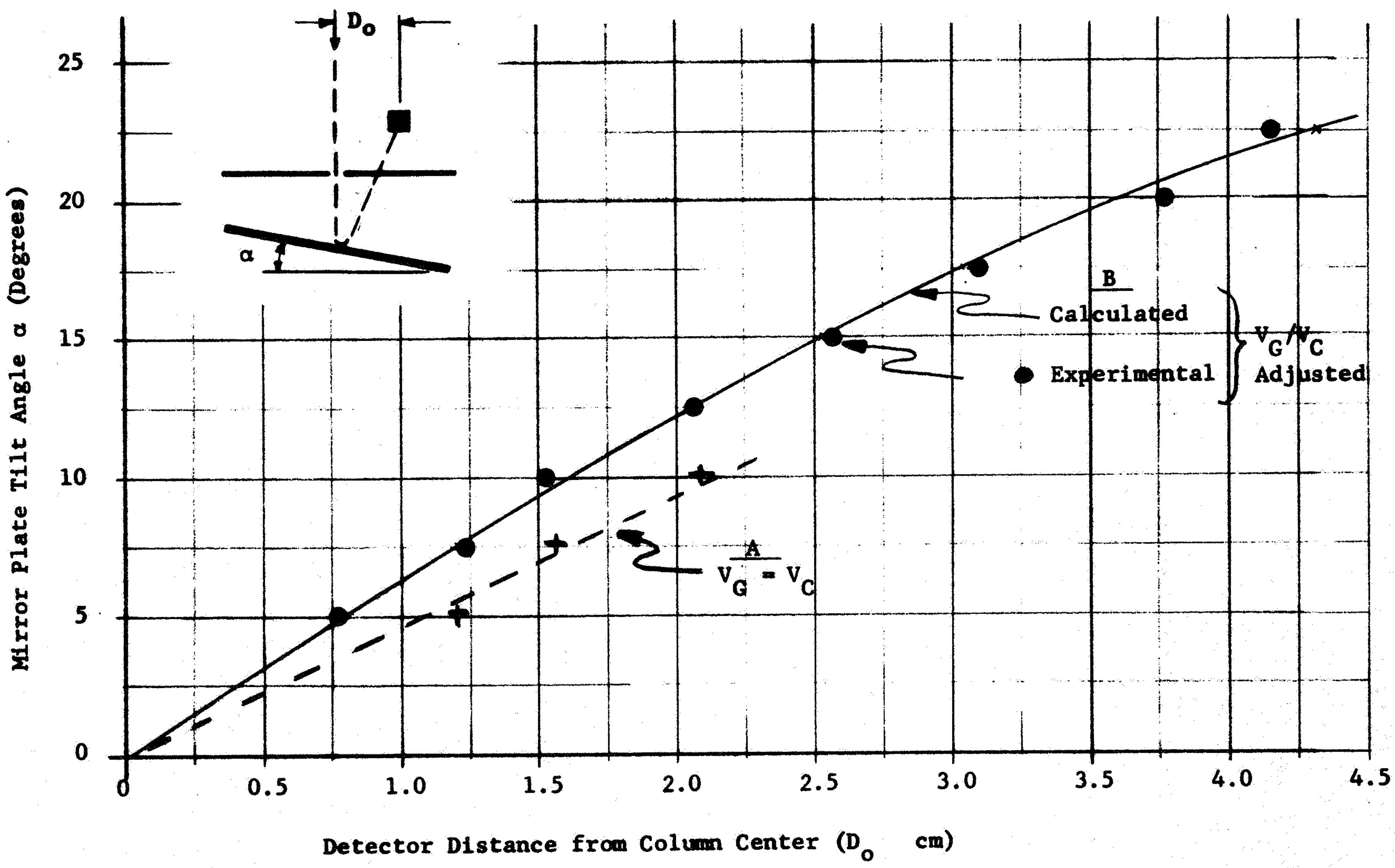


Fig. 5 Electron Mirror-Calculated and Experimental Trajectory Parameters
A. $V_G = V_C$
B. V_G/V_C adjusted for electron reflection at mirror plate surface

expected. For best resolution, the mirror potential should be adjusted so as to allow the electron trajectory vertex to be as close to the specimen surface as possible. The results are also shown in Figure 5.

In all of these experiments, the beam diameter of the reflected electrons, measured with a fine detector wire, was less than 250μ when a 25-30μ beam was focused at the mirror.

The electron beam aperture angle below the final lens is approximately 3×10^{-3} radians and the electron beam diverges by the same angle after reflection at the mirror. The reflected beam diameter, therefore, increases as a function of distance from the focal plane (also mirror plane). A rough calculation indicates that its diameter at the detector should be of the order of 200μ in good agreement with the size measured.

These experiments proved that a sharp, reflected electron beam may be traced along a parabolic path which varies with mirror tilt angle. The relation between the voltage on the electron gun and that on the specimen (mirror) also seems to follow the theoretical expressions which were described previously. The use of the secondary electron emission in obtaining a fine adjustment of the mirror potential was an important, but unexpected, development which should aid instrument alignment. A simple procedure for determining the proper mirror potential under a given set of conditions would now seem to be possible.

Detection of Sample Potential Gradients

The reflection trajectories of the electron beam were also investigated when a simple electric field gradient was applied to the sample. The specimen consisted of a thin copper film, vapor deposited on a thin microscope cover glass. The copper film was bisected by a 200 micron wide gap (see Figure 6), which was subsequently coated with a thin, high resistance carbon film. Side B of the Cu film specimen was connected directly to the electron mirror cathode (at -6,000V), while side A was connected to a variable voltage source floating at the mirror cathode voltage level. A potentiometer allowed the application of various negative voltages across the gap between the two copper film sections, thus establishing adjustable electric gradients across the gap. The experiments were performed with a mirror tilt of 2°. A schematic of the experimental arrangement is shown in Figure 7.

The specimen was traversed beneath the incident electron beam using the stage drive, while the reflected electron beam was intercepted by the movable wire detector previously described. Figure 8 is a plot of the horizontal position of the detector measured from the incident electron beam position (D_o) as a function of the location of the electron beam parabolic vertex just above the specimen surface. Results for various voltage differences (potential gradients) across the gap are plotted.

It is useful to express the electric potential gradient produced along the sample surface as a percentage of the axial potential field of the mirror. The axial potential field is simply the voltage difference between the mirror and the nearest electrode divided by the distance between them. The sample electric potential gradient is the voltage drop applied across the specimen divided by the gap distance. If the sample potential gradient is small compared to the axial field gradient then the vertex of the electron parabola is close to the specimen and

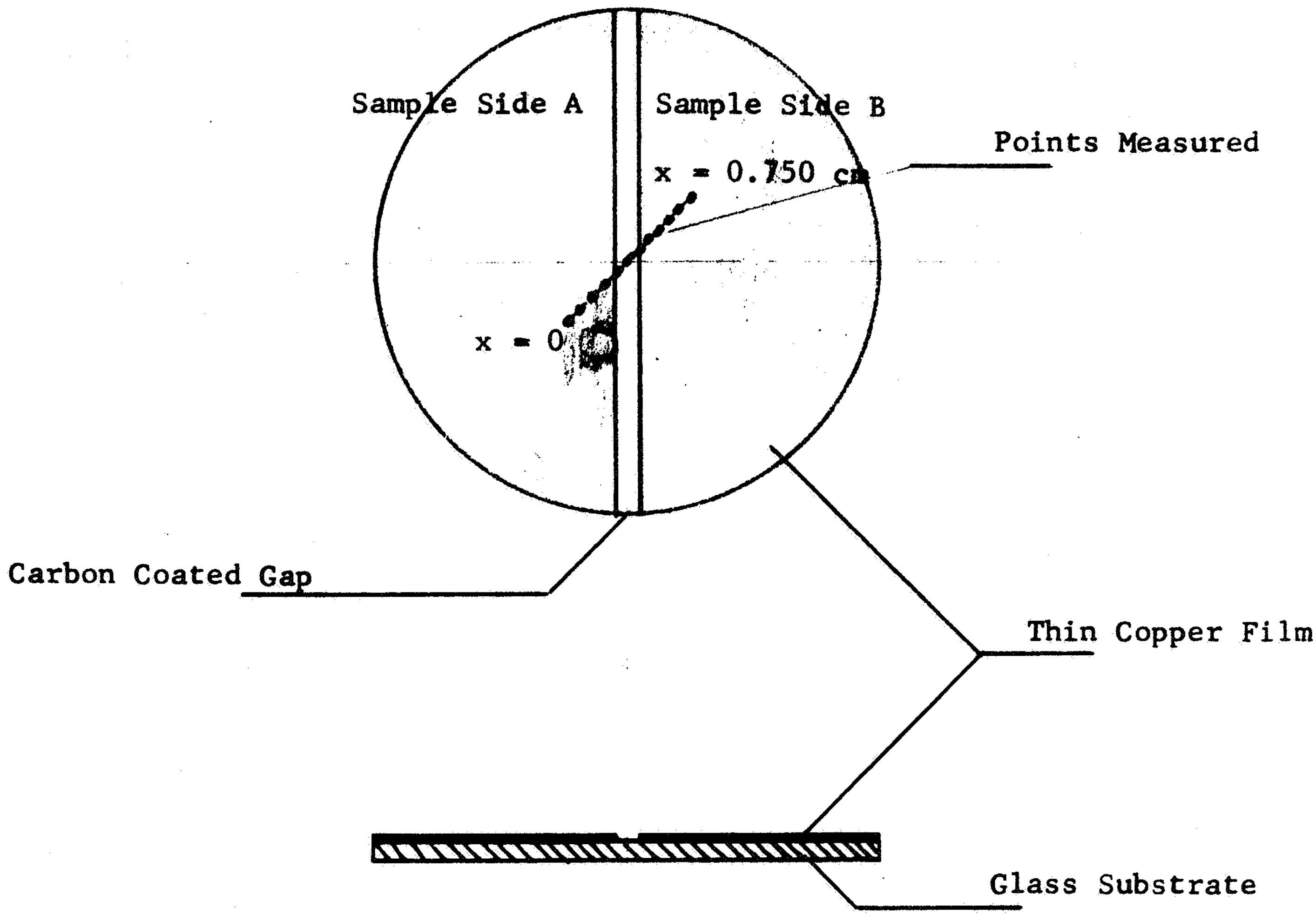


Figure 6 - Thin Film Sample Employed to Analyze
Sample Electric Field Gradients

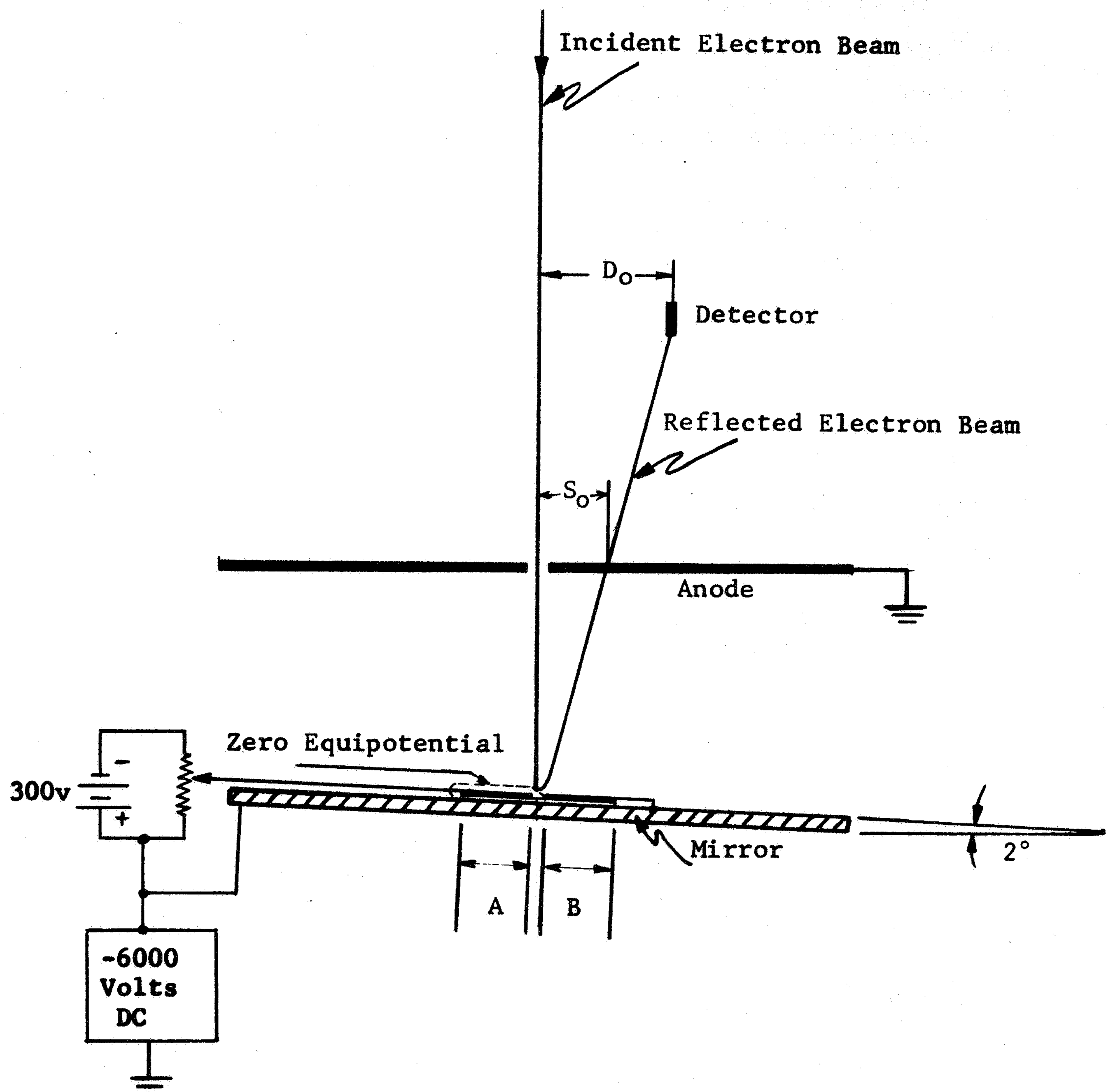


Figure 7 - Schematic of Electron Mirror Arrangement for Detection of Sample Electric Field Gradients

resolution of the gradient shape (determined by the sharpness of the changing electron trajectory) is good.

These experiments were performed at a mirror decelerating voltage of -6,000 volts which is equivalent to an axial field gradient of -3,000 volts/cm. It is obvious from Figure 8 that satisfactory gradient resolution is obtained when the sample potential gradient is approximately 1% of the axial field gradient of the mirror. If the gradient magnitude is greater than 1%, the shape of the gradient is not well resolved. If the gradient magnitude is very much less than 1%, then the position and size of the detector would be very critical.

From the standpoint of final mirror design it would seem that sample potential gradients to be investigated should lie within a range of 0.1% to 1% of the axial mirror field gradient.

In the design of a final mirror chamber, the axial mirror field gradient near the sample could be very simply adjusted by varying the voltages applied to a series of grids lying above the mirror in conformity with the results of the analog field plotting experiments discussed earlier. In this way any sample potential gradient of interest could be adjusted to lie within the high resolution range of the mirror. For instance if a very shallow gradient of 10mv/300μ (0.3 volts/cm) were present on the sample surface, it would be well resolved if the potential difference between the mirror and grid No. 3 was adjusted to some value between 30 and 300 volts.

It is interesting to note that sample potential gradients have a smaller influence on the electron beam trajectory than sample tilting. Although the sample potential gradient of 0.5% in Figure 8 produces a tilt of the zero equipotential line of

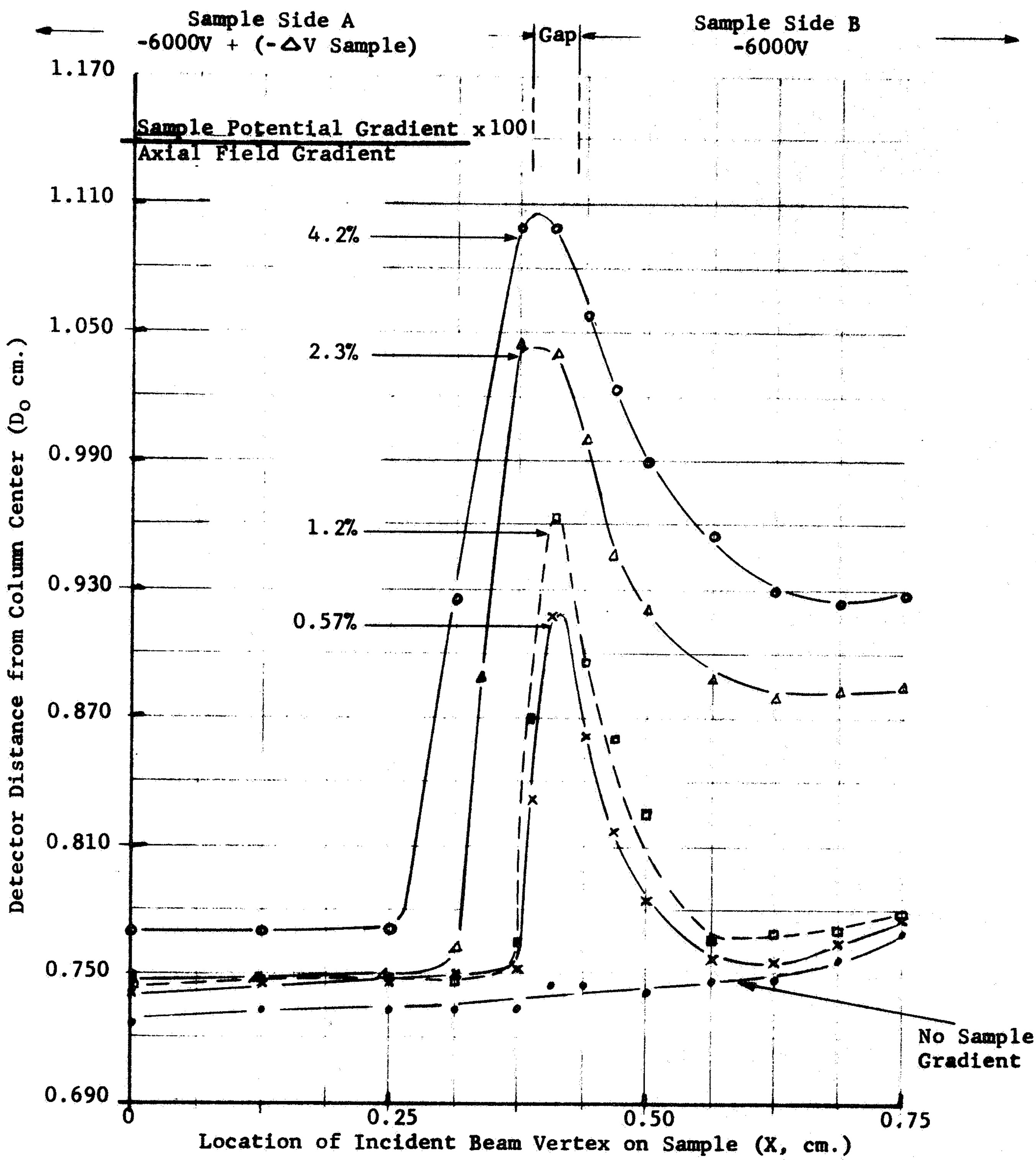


Figure 8 - Measurement of Electric Field Gradients. Position of Electron Beam Reflection on Sample vs. Electron Detector Intercept Distance D_O, for Several Ratios of Sample Potential Gradient/Axial Field Gradient Axial Mirror Field = 3000V/cm.

about 10°, the net horizontal electron deflection at the detector is only about 0.2 cm. If the mirror itself is tilted 10° the corresponding electron deflection is about 2 cm. It is obvious that the influence of a local potential gradient on the sample surface does not extend to distances much above the sample surface. It is the sample tilt which mainly controls the electron trajectory in the electron mirror.

Scanning Display System

The scanning system was examined in order to determine whether the scan rate was linear with deflection (uniform magnification across the field of view). In addition, the effect of varying axial field gradients within the mirror on the scanning characteristics was also studied. A wire mesh mounted to the cathode plate of the mirror served as a sample. Figure 9 shows a photomicrograph of the mesh taken at a magnification of approximately 250X.

<u>Line Scans</u>.- The electron beam, approximately 10μ in diameter, was electromagnetically scanned, in a line, across the grid, while the mirror reflection plate was connected to the input of the signal processing amplifier. No high voltage was applied to the mirror.

The oscilloscope trace in Figure 10 depicts the electron current absorbed by part of the sample. The magnification and signal strength across the scanned field seems uniform for similar sample areas.

The electron mirror plate containing the sample was then connected to the high voltage supply (mirror operation). The

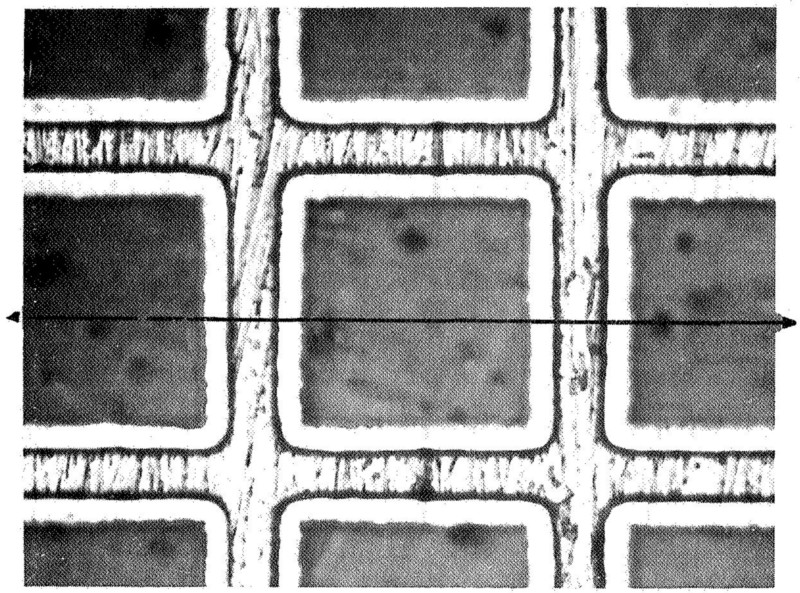


Fig. 9, Photomicrograph of Cu-Grid, ~ 250X

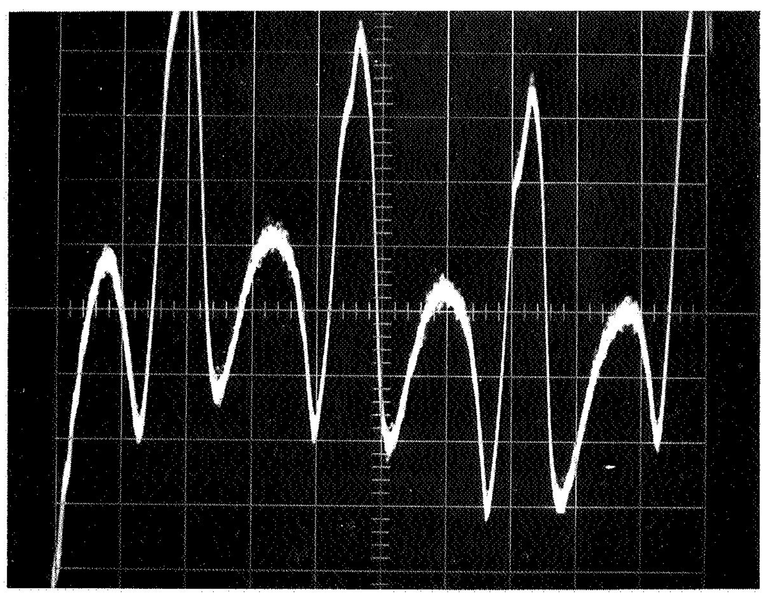


Fig. 10, Line Scan - Absorbed Electron Current

V_{Gun} = 6 KV, V Mirror = 0

Electron Beam Diameter at Sample Approx. 10μ, ~ 140X "reflected" electron beam was then collected on a rectangular detector located 1 cm above the anode plate of the mirror, at a distance of 4.5 mm from the electron optical axis. The signal collected by the detector is shown in Figure 11. The magnification and signal strength is again satisfactorily uniform across the scanning field.

Raster Scans.- In order to produce a two-dimensional image of the sample on the cathode ray tube, the electron beam is scanned in two mutually orthogonal directions and the Z-axis of the oscilloscope is modulated by the signal produced by electrons absorbed in the sample in the case of specimen current images and by the signal reflected by the sample and received at the detector in the case of reflected electron beam images. The specimen current images are obtained with the specimen at ground, while the reflected electron images are obtained with the sample at high voltage. Figure 12 shows a raster scan of a copper grid, produced by absorbed electron current signals (180X) with a lens working distance of 1.5 cm. This results in an electron beam spot size of approximately 1 micron. The image quality is excellent.

Figures 13a and 13b show the image of the copper grid as produced by the prototype Scanning Electron Mirror Microscope in the reflective operating mode. The video signal was derived from a very small rectangular metal detector situated 1 cm above the anode. The voltage applied to the reflection plate of the mirror was such as to reflect the entire incident electron beam within a distance of 5 microns above the lowest sample surface. The mirror reflection plate (including the sample) was tilted by an angle of 2° towards the detector.

The final lens working distance in this mode was 4 cm, which

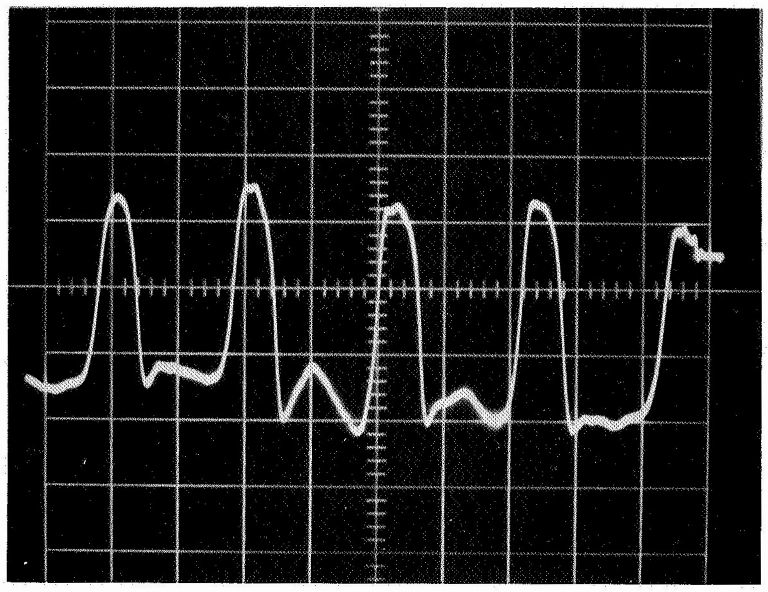


Fig. 11, Line Scan - Reflected Electron Current

V_{Gun} = 6 KV, V Cathode = -6 KV

Detector - Incident Beam Distance D_o = 4.5 mm, ~ 120X

Fig. 12, Raster Scan Across a Cu-Grid, Absorbed Electron Current, 180X resulted in a spot size at the sample surface of about 10 microns. Again the magnification seems uniform across the field, the signal strength is uniform and distortion of any kind is at a minimum (even for 60X).

Apertures in Electron Mirror Anode and Grids

It had been proposed that the electrons reflected and/or scattered by the sample would exit the electron mirror through a highly transmittant wire screen placed in the anode and/or grids. The main purpose of the screen was to maintain a uniform axial potential field throughout the mirror chamber even while cutting holes to allow exit of the reflected electron beam. This would enhance the electron scatter contrast observed since the detector could be placed far above the mirror surface.

Tests were performed in a search for possible distortion effects of the electron reflection image produced by this wire screen in the anode. It was found that when the incident electrons were allowed to impact on the sample surface at energies greater than zero (by adjusting the voltage on the sample) secondary electrons were produced. These electrons were collected and images could be formed. The low energy secondary electrons are accelerated towards the anode or detector over a wide area. Most of the electrons pass through the high transmission screen and impact on the detector. Since the instantaneous video signal is made up of electrons passing through many holes in the screen at once, the image of the screen is not "superimposed" on the image of the sample. Only the signal intensity is negligibly reduced. Figure 14a shows the image of "pin holes" in the mirror reflection plate. The incident electrons were allowed to enter the sample with an energy of 10 volts, (voltage difference of gun and mirror) and the low energy secondaries produced were accelerated towards the detector and passed through the holes in the anode screen. The image is undistorted.

However, when the sample voltage is adjusted to produce electron reflection at or above the sample surface, the reflected beam near the anode has a definite small diameter (in the present instrument about 200-250μ). As the incident electron beam is scanned across the sample, the reflected beam is traversed at the same rate across the wire screen in the anode. Thus, the 200μ beam at the screen will be prevented from reaching the detector when a solid screen wire is crossed during scanning. It was found also that the field perturbations about the wire screen distorted the image.

An example of an image formed during this experiment is shown in Figure 14b. An image of the pin holes on the sample surface and a distorted image of the screen at the anode are superimposed.

This experiment indicates clearly that a wire screen material should not be utilized in the construction of the final electron mirror as a transmission media in the anode or grids for reflected electrons.

Image Resolution and Contrast

The effect on the scanning image quality of variations in detector size, position and shape along with absolute mirror voltages (axial field gradient) was investigated in a series of experiments.

As the mirror surface potential is made more negative the reflected electrons will turn around at distances farther and

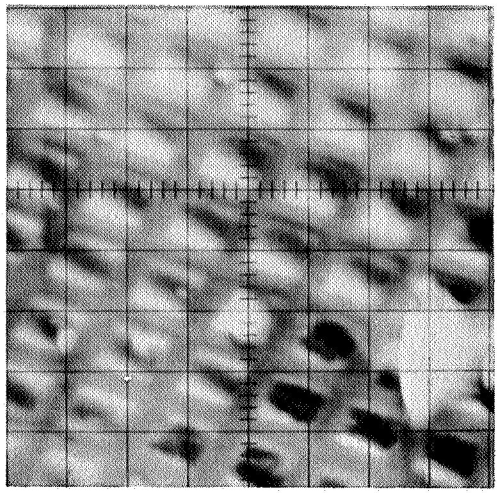


Fig. 13a
~ 60X

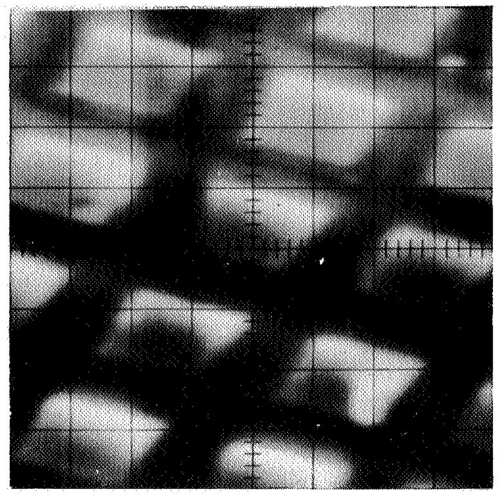


Fig. 13b
~ 150X

Scanning Electron Mirror Microscope Images of a Copper Grid

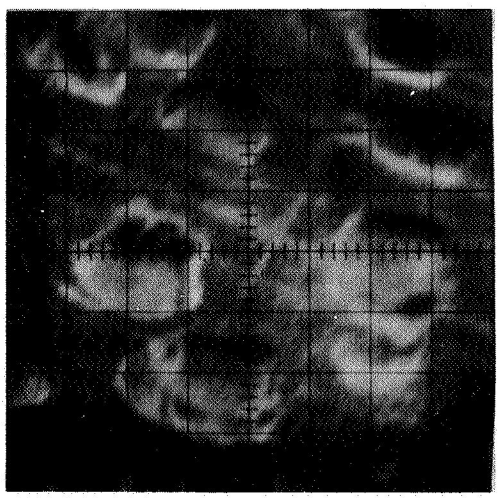


Fig. 14a
~ 80X

Electron Impact Energy
~ 10 ev

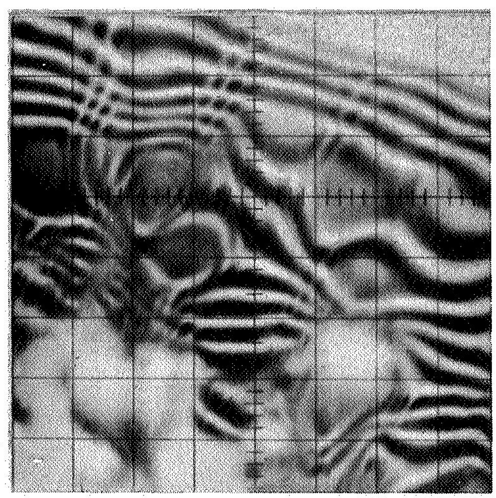


Fig. 14b
~ 80X

Electrons Reflected Within
~ 2μ Above Sample

Image distortion effect of wire screen placed in the anode plate of the mirror. Electrons pass through screen to detector.

Detector Position 1	D_o = 2.3 mm
Detector Position 2	D_o = 4.06 mm
Detector Position 3	D_o = 5.35 mm

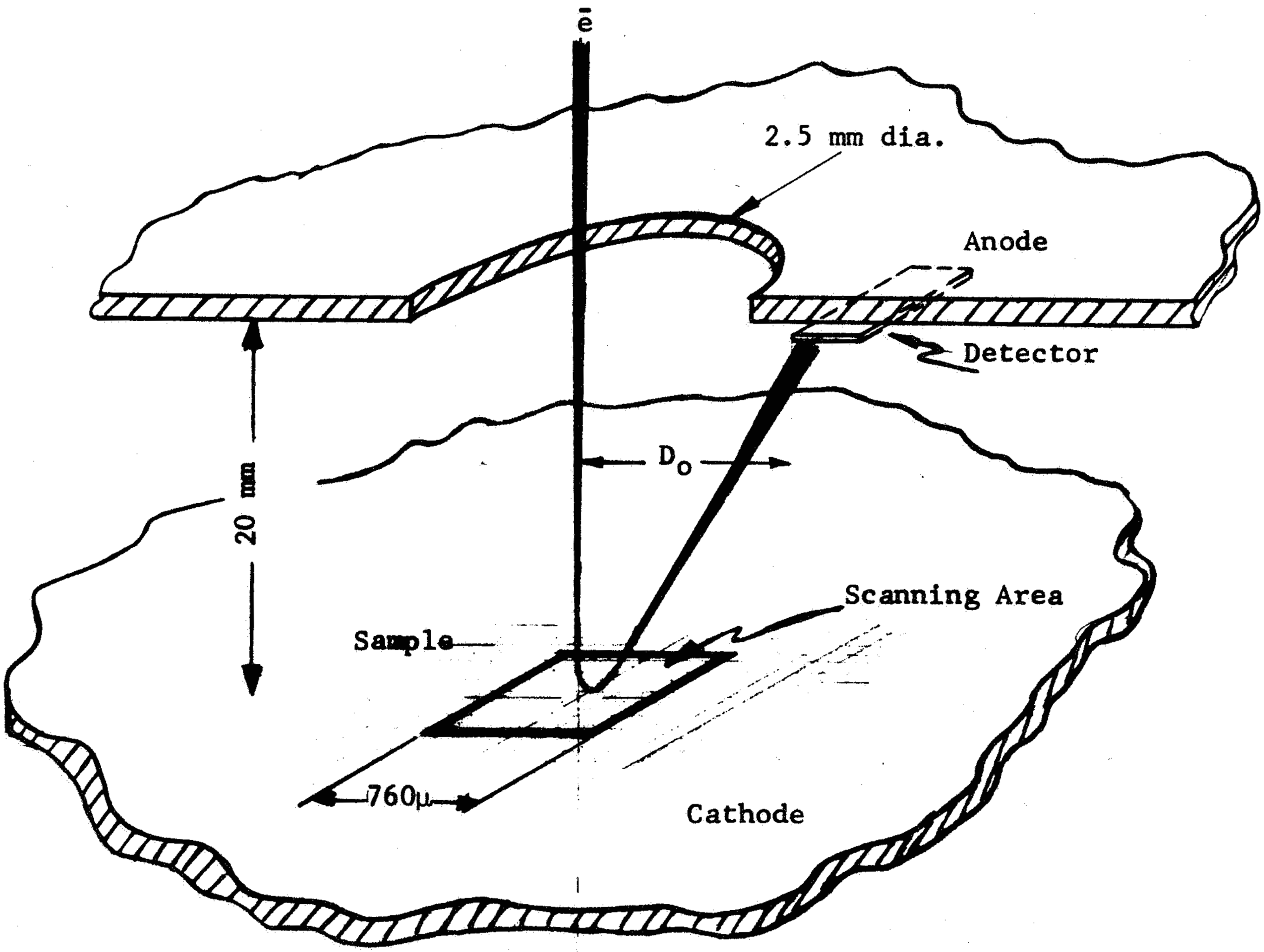


Fig. 15 Geometrical Arrangement of Electron Mirror and Detector for Image Resolution and Contrast Studies. Detector below anode plate.

farther above the sample surface. It might be anticipated that the equipotential surface becomes flat high above the surface and resolution is lost. If the mirror is slightly positive in voltage with respect to the gun, electrons will strike the surface with a slight excess energy. Under these conditions, secondary electrons are produced and accelerated towards the anode.

The position of the detector is also important. If the detector is translated away from the reflected beam only those electrons which are reflected at large angles with respect to the normal beam (flat potential surface) may be intercepted. In this case, image contrast will be high but absolute signal levels could be low. The detector shape is also important. If it is elongated in one direction only, electrons scattered perpendicular to its long direction may be lost and only one dimensional structure will be observed.

The voltage on the mirror was varied in discrete steps so as to include both the reflection and secondary electron producing modes of operation. The reflection plate of the mirror was tilted toward the detector by one degree and a thin (3 mm wide, 1-1/2 cm long) metal plate detector was placed directly below the anode. The anode plate consisted of a solid metal sheet with a 2.54 mm diameter hole for entrance of the electron beam.

Three detector positions were chosen which were representative of the range within which reasonable images could be obtained both for reflected electrons and for secondary electrons. The geometry of the mirror/detector configuration is shown in Figure 15.

Detector Position 1, D_o = 2.3 mm.- At this position, the detector is about as close to the incoming beam as possible and consequently quite far from the position at which it would intercept the normally reflected beam.

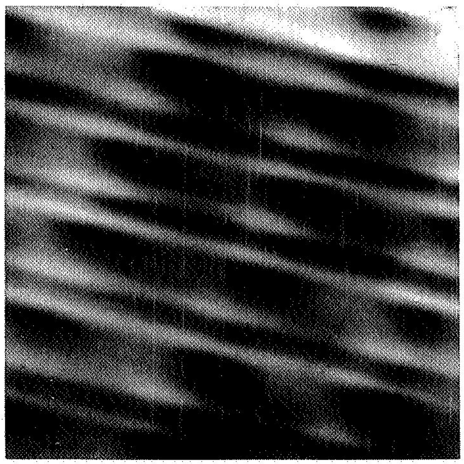
The series of micrographs shown in Figure 16 start with the condition in which the beam enters the specimen at a slight excess energy and therefore produces secondary electrons (Figure 16a). The electrons are accelerated almost straight back towards the anode and a strong signal is seen by the detector.

The image is essentially one dimensional in Figures 16a, 16b, and 16c. The detector, since it is elongated, receives all the electrons scattered or reflected in one direction, but only a fraction of these scattered or reflected in the other direction. In the full reflection mode, Figures 16c and 16d, the image is weaker since most electrons are reflected towards position 3 of the detector. When the electron beam is reflected "high" above the sample surface, the image is uniform. This is because the zero equipotential surface is also uniform at this level.

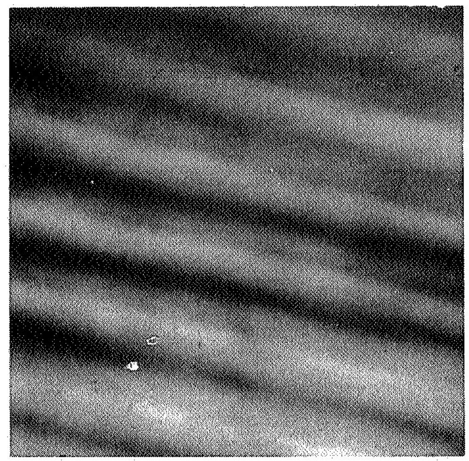
It should be noted that dark areas in these images correspond to the presence of electrons and light areas to the absence of electrons.

<u>Detector Position 2, D_o = 4.06 mm.</u>- The secondary electron pictures of Figures 17a and 17b show a little more contrast than those of Figure 16. This is because the detector is positioned so as to intercept highly scattered secondary electrons. The reflection images (Figures 17c and 17d) are virtually the same as those of Figure 16.

<u>Detector Position 3, D_o = 5.35 mm</u>.- The secondary electron images (Figures 18a, 18b) are of poor quality. The detector is far from the strong secondary electron beam and high signal amplification is required. Some amplifier noise does distort the images.

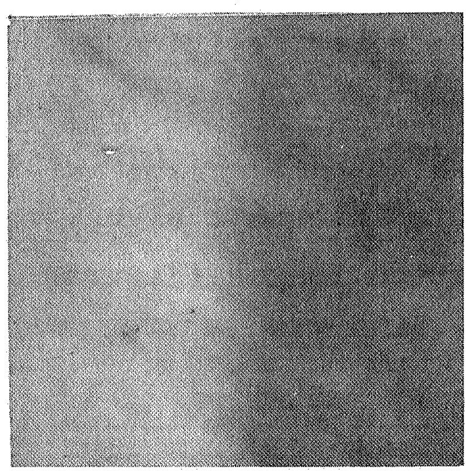


a) Electron Impact Energy
$\sim$200 ev



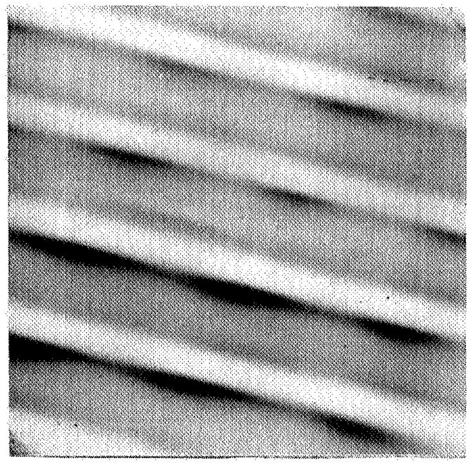
b) Electron Impact Energy
$\sim$ 50 ev

c) Electrons Reflected
$\sim$10μ Above Sample Surface



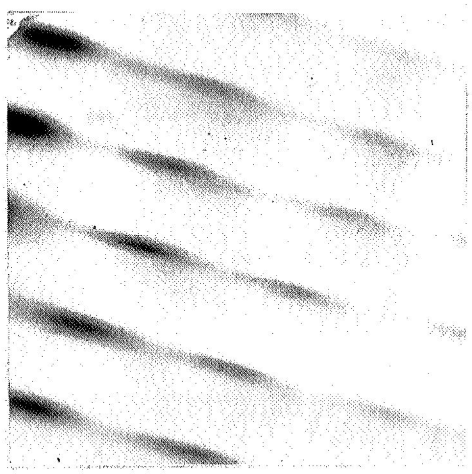
d) Electrons Reflected
$\sim$50μ Above Sample Surface

Fig. 16, Scanning Electron Mirror Microscope Images.
Detector Position 1, D_o = 2.3 mm, $\sim$100X
Magnification (See Figure 15).

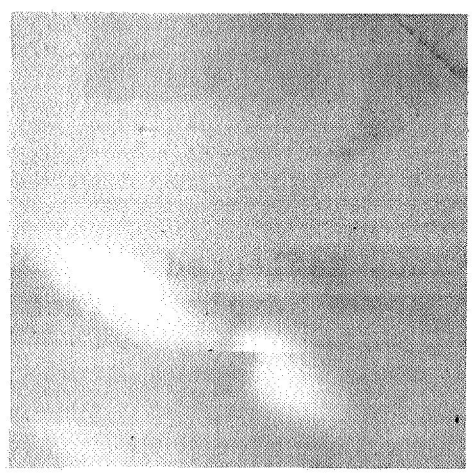


a) Electron Impact Energy
$\sim$ 200 ev

b) Electron Impact Energy
$\sim$ 50 ev



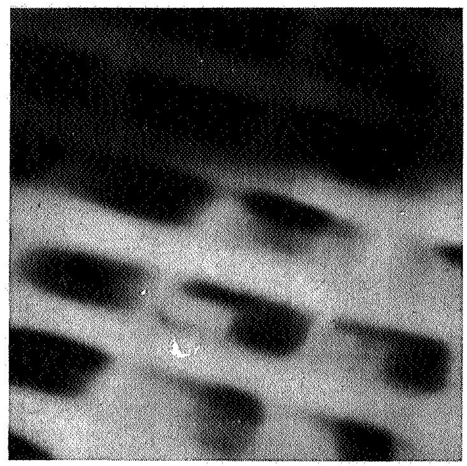
c) Electrons Reflected
$\sim 10\mu$ Above Sample Surface



d) Electrons Reflected
$\sim 50\mu$ Above Sample Surface

Fig. 17, Scanning Electron Mirror Microscope Images. Detector Position 2, D_o = 4.06 mm, $\sim$100X Magnification (See Figure 15).

a) Electron Impact Energy
$\sim$ 200 ev



b) Electron Impact Energy
$\sim$ 50 ev

c) Electrons Reflected
$\sim 10\mu$ Above Sample Surface

d) Electrons Reflected
$\sim 50\mu$ Above Sample Surface

Fig. 18, Scanning Electron Mirror Microscope Images. Detector Position 3, D_o = 5.35 mm $\sim$100X Magnification (See Figure 15).

The reflected electron images (Figures 18c, 18d, 18b) show very poor contrast across the grid wires or grid openings. The main reflected beam, from the holes, is received uniformly by the detector. Practically none of the electrons incident just above the wires are seen by the detector.

It appears that a final, optimum detector design should allow the possibility of changes in size, shape, and position. In addition, the mirror should be operated variably in either the reflected electron mode or in that condition which allows the electrons to strike the sample with a few electron volts of energy. In this case the penetration is only a few angstrom units and the characteristics of the images are very informative.

DESIGN PROPOSAL FOR A SCANNING ELECTRON MIRROR MICROSCOPE

Based on the analog field plotting experiments and those with the prototype instrument, a comprehensive design for a complete Scanning Electron Mirror Microscope system is proposed. This instrument would incorporate all of the design innovations and technology available at this time. It should be pointed out, however, that the concept of this instrument is still quite new, and the design suggested represents only a beginning in what could very well be a greatly expanding interest in the mirror microscopy technique.

System Concept

The entire system concept proposed in this design is shown in the form of a schematic block diagram in Figure 19. Individual subsystems are discussed further in other sections of this report.

Electron Optical Column and Electron Mirror Specimen Chamber

The electron optical column proposed (shown in Figure 20) contains one of the following design features.

Electron Gun.- This assembly allows the cathode to be tilted and translated horizontally. The entire emission chamber is hinged and can be swung into a horizontal position for easy filament changes.

The anode height can be adjusted to produce various cathode to anode spacings between 1 and 12 mm.

Alignment Coils.- Four electromagnetic alignment coils aid column alignment substantially.

Key to Schematic Block Diagram of Figure 19

1 - Electron Gun

2 - Alignment Coils

3 - 1st Condenser Lens

4 - 2nd Condenser Lens

5 - Electron Beam Scanning Coils and Stigmator

6 - Objective Lens

7 - Electron Detectors

7a - Video Preamplifier

8 - Electron Mirror

9 - Vacuum System

10 - Detector Selectors

11 - Video Amplifier

12 - Vacuum System Control

13 - Video Amplifier Power Supply

14 - Vacuum System Power Supply

15 - Spare

16 - Scan Current Amplifiers

17 - Time Base Generators

18 - Blanking Networks

19 - CRT Display Unit

20 - Magnification Control - Scan Coils DC Control

21 - Electron Beam Alignment Coils - Power Supply

22 - Lens Controls

23 - Power Supply - 1st Condenser Lens

24 - Power Supply - 2nd Condenser Lens

25 - Power Supply - Objective Lens

26 - Electron Gun Filament Supply

27 - H.V. Power Supply

28 - Power Supplies for Specimen (at Mirror Potential)

29 - Electron Mirror - H.V. Controls

30 - Spare

31 - Line Voltage Stabilizer

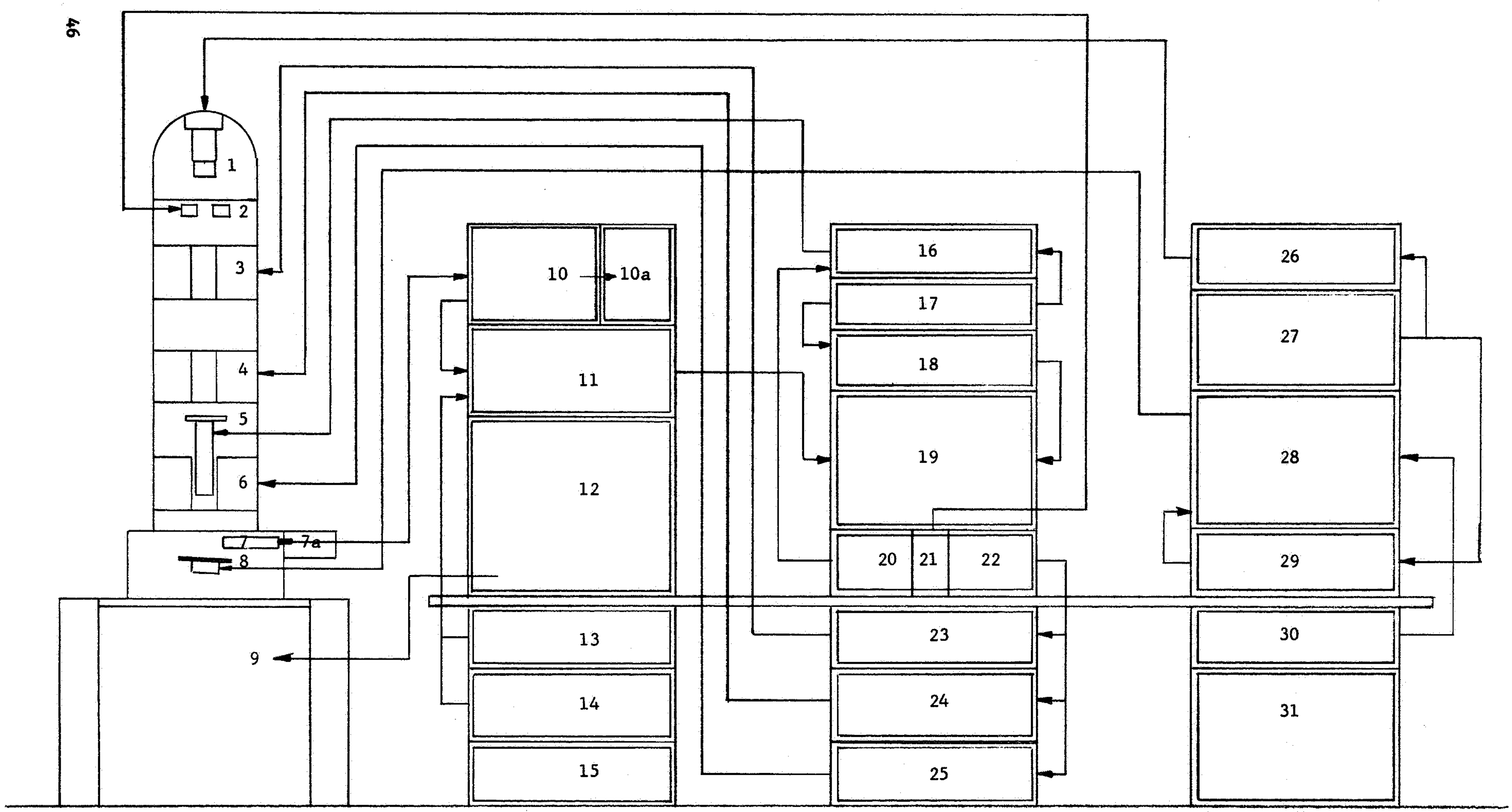


Figure 19 Schematic Block Diagram AMR Scanning Electron Mirror Microscope

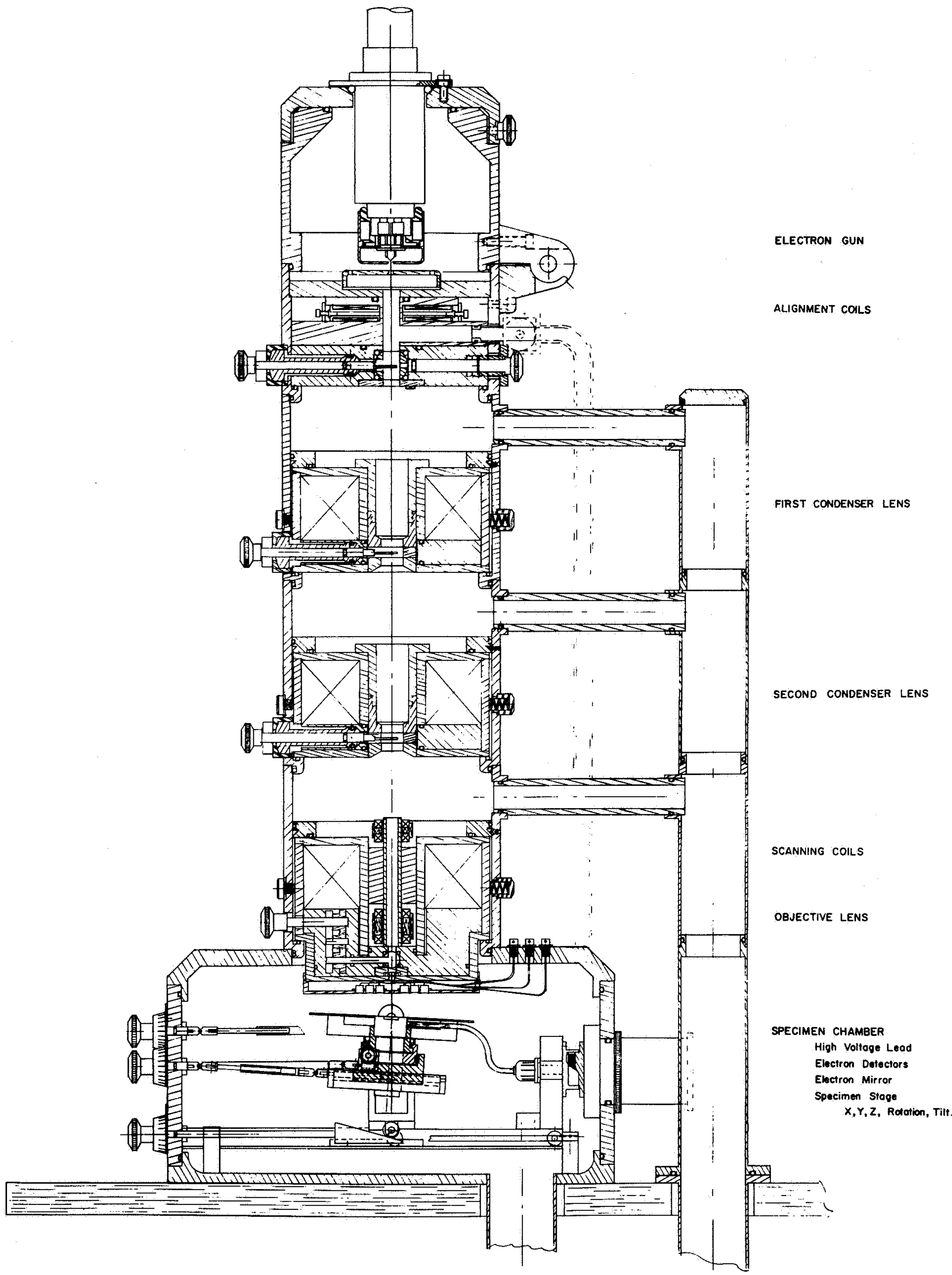


Figure 20 AMR Scanning Electron Mirror Microscope

Aperture/Ball Valve.- A combined aperture and ball valve is situated below the alignment coil assembly. This valve allows isolation of the gun chamber and therefore speedier filament replacement procedures.

Lens Housings.- All three shells containing the electromagnetic lenses are identical and therefore interchangeable in accord with an attempt to produce a modular design.

Electromagnetic Lenses.- The lenses are easily removed from the lens housings. For alignment purposes, the lens assembly can be traversed plus or minus 1 mm. As shown in Figure 21, the lens winding is operated in air, external to the vacuum chamber. The pole piece assembly in both condenser lenses can be removed after the aperture rod is retracted.

The objective lens differs from the condenser lenses because of the accommodation of the scanning coils and the stigmator, its protrusion into the specimen chamber to achieve a shorter working distance, and the accommodation of a vacuum isolation ball valve.

Lens Chamber Valve.- The ball valve contained within the objective lens assembly allows isolation of the specimen chamber from the column assembly.

Electron Mirror - Specimen Chamber.- The specimen chamber contains the specimen stage, which can be removed from the column on a sliding track assembly. The specimen holder which also contains the electron mirror cathode, can be raised, tilted, traversed in an x and y direction and rotated.

The specimen and the mirror cathode plate are connected to the high voltage supplies and the sample test circuit power

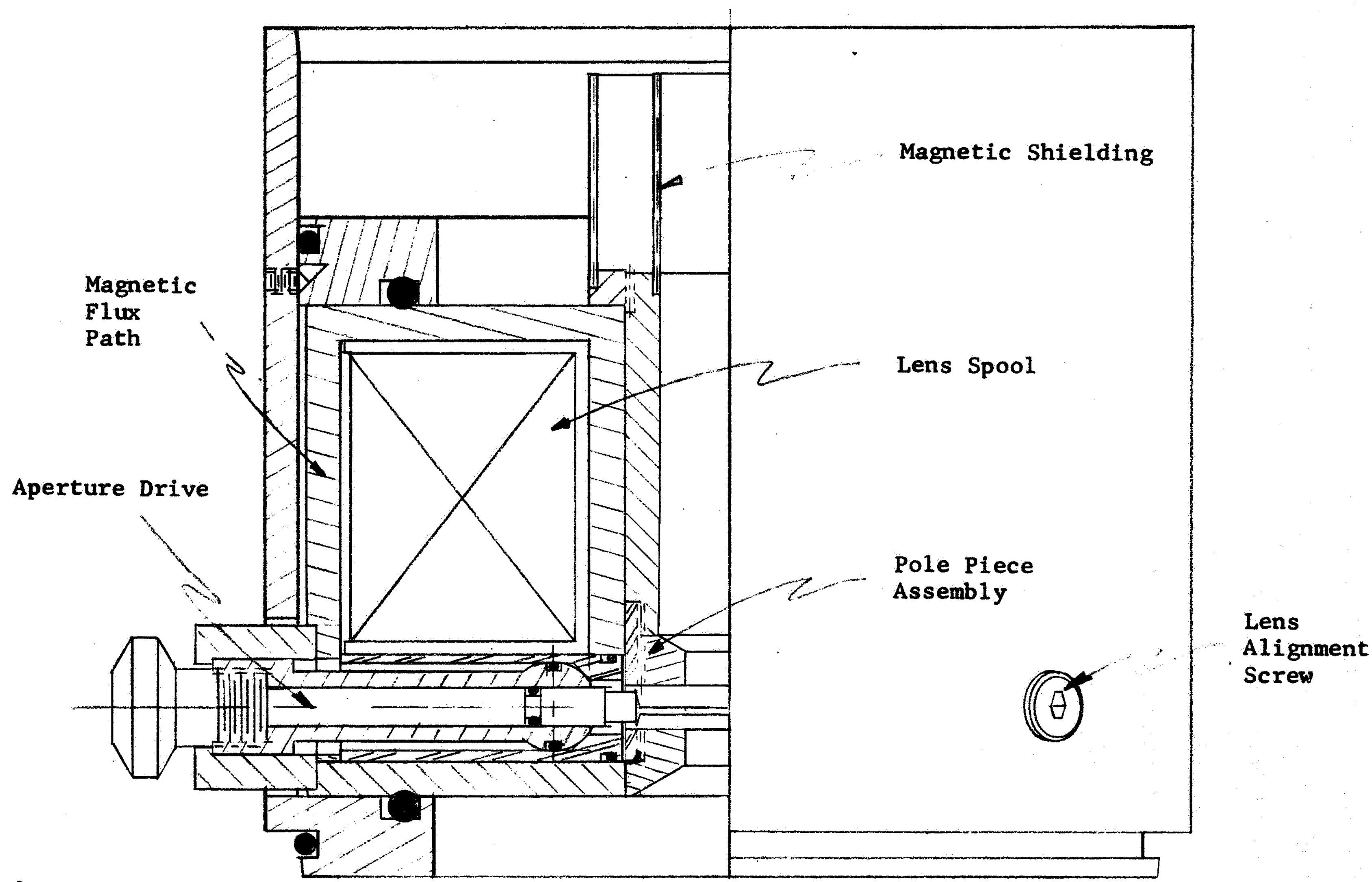


Figure 21 Cross Section of Modular Condenser Lens

supplies via a multi-connector and a high voltage feedthrough.

The electron mirror anode is mounted rigidly to the bottom of the objective lens. The anode accommodates the solid state electron detector array.

Three major vacuum connections are made to the column at the specimen chamber, the lens chamber and the gun chamber.

<u>Column Support</u>.- The instrument column is mounted to the cabinet which contains the vacuum system and its controls. The cabinet is supported by shockproof mounts to eliminate unwanted vibrations.

DETAILED SYSTEM COMPONENT SPECIFICATIONS FOR PROPOSED INSTRUMENT

Electron Gun and Mirror High Voltage Supply

This system is composed of a few sub-supplies which are arranged as shown in Figure 22. A voltage divider network allows the selection of any one of a number of fixed absolute potentials covering a range of voltages lying 1% more negative and 5% more positive than the electron gun potential. Once this potential has been obtained it may be varied over a fine range of plus or minus 250 mv. This would allow operation of the electron mirror in a true reflecting mode and also in a fashion which produces secondary electrons. A wide-range electrostatic voltmeter (M_4) indicates the potential difference between the electron gun and mirror.

High Voltage Supply.- The basic high voltage supply is a Power Designs No. 1584 air operated unit utilizing a 220 volt AC input. The output is 1-20 KV and 0-3 ma. Stability is 26 ppm/ 10 min. at 20 KV and the ripple is 300 mv.

Filament Power Supply.- The output of this unit, which is isolated for 20 KV is 0-10V DC at 0-10 amps. Ripple is less than 5%. An adjustable bias resistor (0-2 megohm, 5 watts) is situated between the high voltage power supply and filament power supply. A meter is supplied to monitor the primary current in the filament supply.

Sample Power Supplies.- These supplies which would power electronic device samples are isolated for 30 KV. Three separate units will be used with 220V AC input and 0-46V DC, 0-500 ma output with 0.005% regulation.

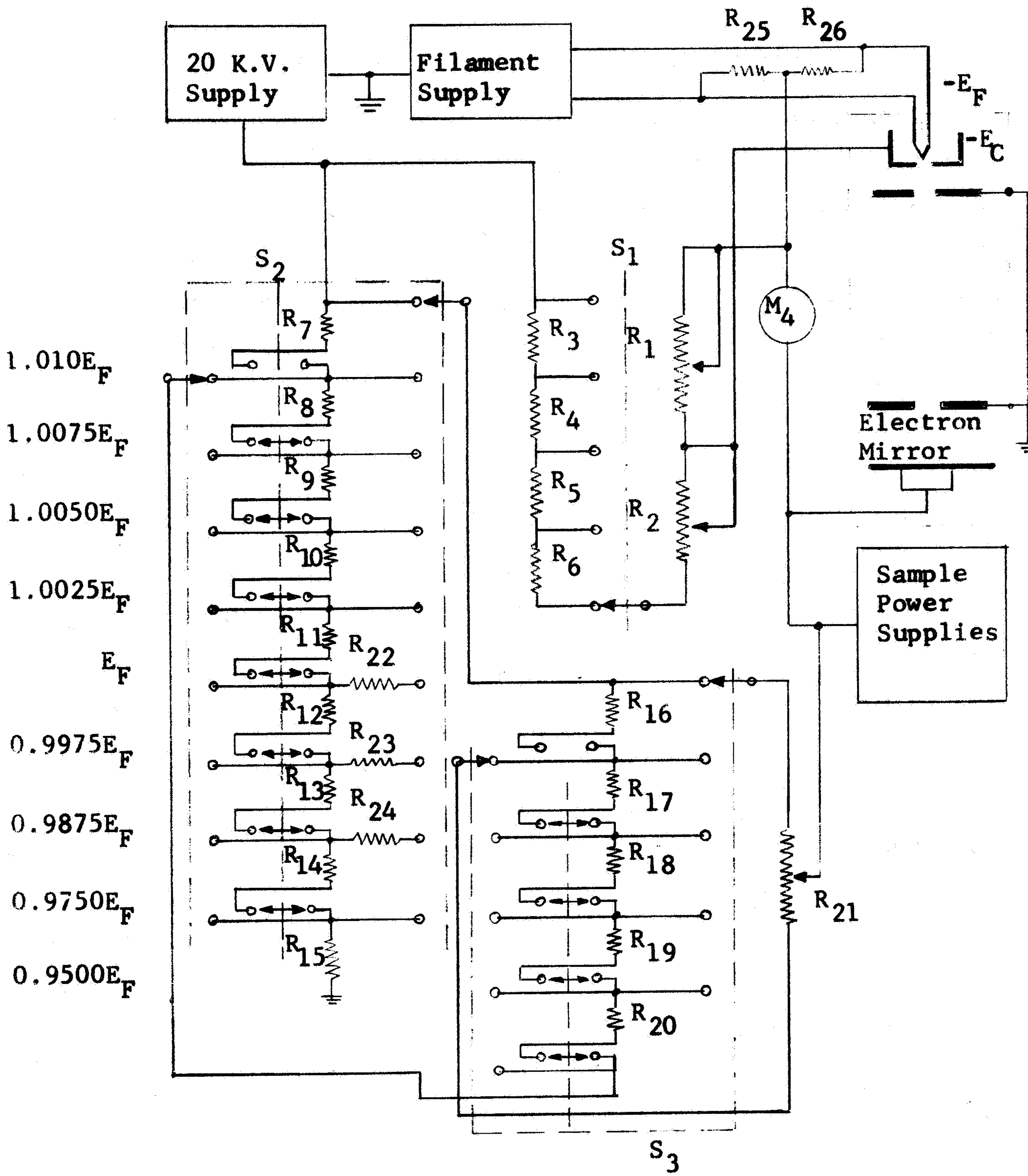


Figure 22 Schematic Diagram - High Voltage System Scanning Electron Mirror Microscope

Electron Mirror Supply.- Potentials for the electron mirror will be derived from the high voltage power supply via a continuously adjustable voltage divider. The electron mirror voltage range will be 101%-95% of filament potential. One wide range electrostatic voltmeter will be connected between the electron gun filament and electron mirror.

Electromagnetic Lenses and Lens Power Supplies

Lenses.- The lens excitation parameters for all three lenses will involve a maximum lens current of 0.5 amperes and a $Vr/(NI)^2$ of 0.0125. Approximately 4,000 windings will be used. Lens spools will be removable from the main lens housing.

Lens Supplies.- To attain the required stability of the lens excitation current, a standard ultrastable constant voltage supply, Hewlett-Packard Model No. 6102A will be modified for constant current operation (as shown in Figure 23). The current range is 50 to 500 ma. Load and line regulation is 10 ppm and output current stability is 13 ppm/10 min.

Scanning Display System

The concept of the scanning display system is schematically illustrated in Figure 24. The scanning drive signals for either axis (x and y) of the column scanning coils are derived from the sweep generator of the corresponding display axis of the oscilloscope. The raster of the electron beam in the scanning electron mirror microscope is thus synchronized with the raster of the electron beam in the cathode ray tube.

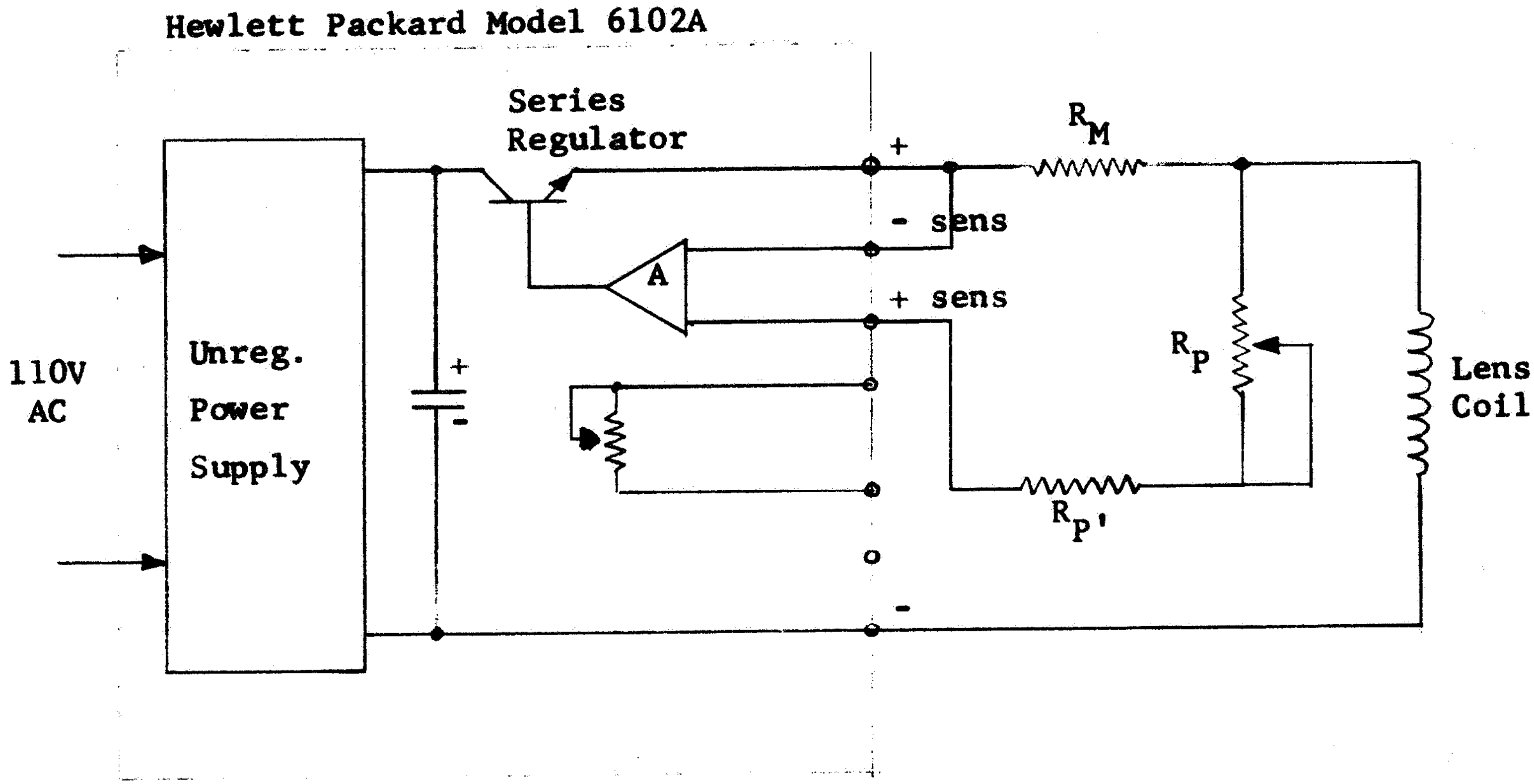


Figure 23 Schematic Diagram - Lens Power Supply - Constant Current Operation

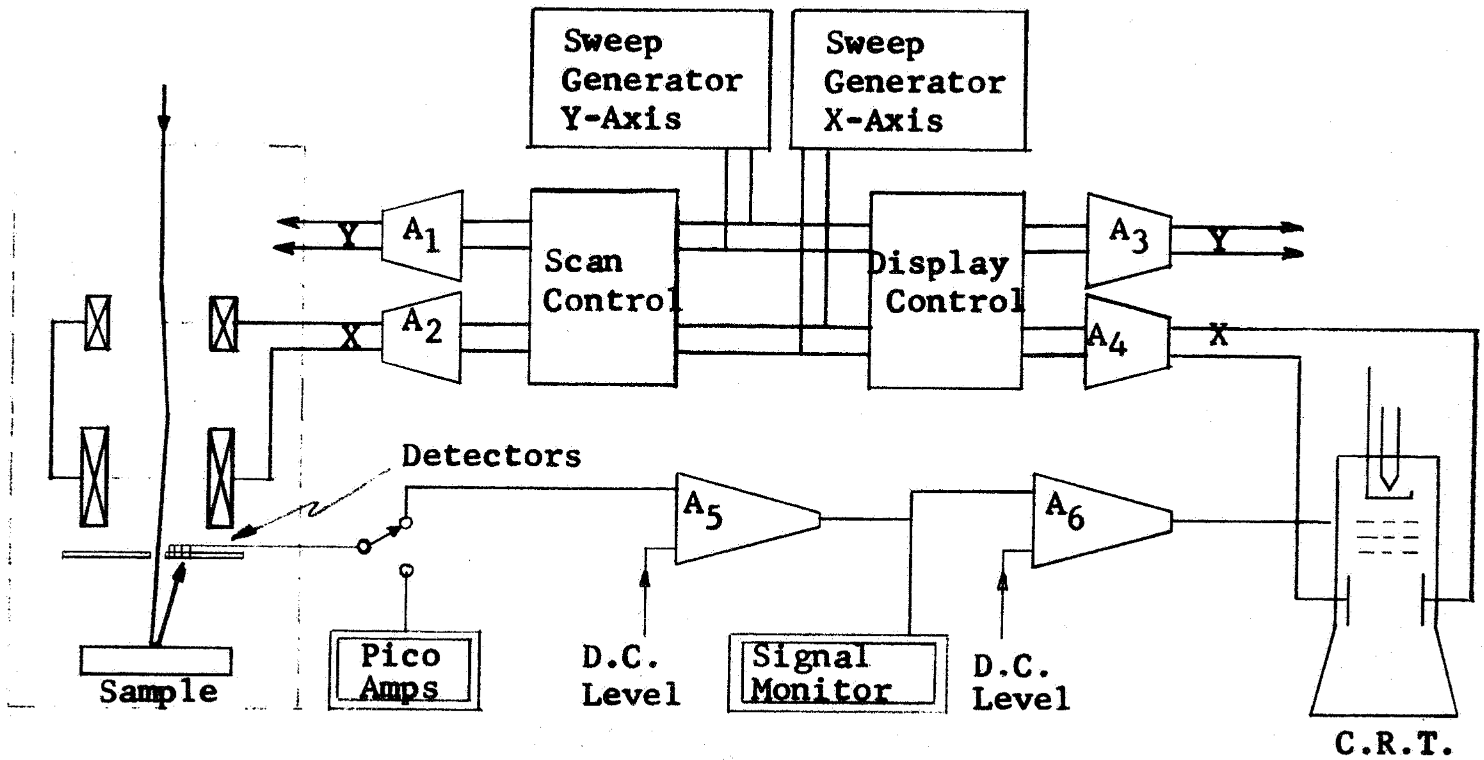


Figure 24 Schematic Diagram - Scanning Display System

Sweep Generator.- The display image is produced by either 250, 500 or 1000 lines per frame. These require particular sweep rates for the x and y sweep generator as given in Table III.

Scan Control Unit.- These circuits control the electromagnetic image-shift facility and determine the instrument magnification. The unit is calibrated to yield thirteen discretely selectable magnifications from 20X to 200,000X at an accelerating voltage of 10 kilovolts.

Sweep Current Amplifiers (A_1, A_2).- A detailed schematic for these amplifiers is shown in Figure 25. This circuit design yields a scan coil current which is in phase with the input voltage, and therefore the deflections on the display oscilloscope.

Display Control, A_3, A_4, Cathode Ray Tube, A_6.- All of these circuits are components of a Tektronix Oscilloscope Type 360 or its equivalent.

Pico Ammeter.- Keithley Model No. 15008 or equivalent.

A_6 Video Preamplifier.- Keithley No. 301 or equivalent.

Signal Monitor Oscilloscope.- Tektronix Model No. 504 or equivalent.

Vacuum System

The vacuum system will be housed in the column support cabinet and will provide pumping connections to the gun chamber, the lens chamber, and the specimen chamber. The pump and valve arrangement (see Figure 26) allows continuous pumping on a partial column, while either the specimen chamber or the gun chamber are aerated.

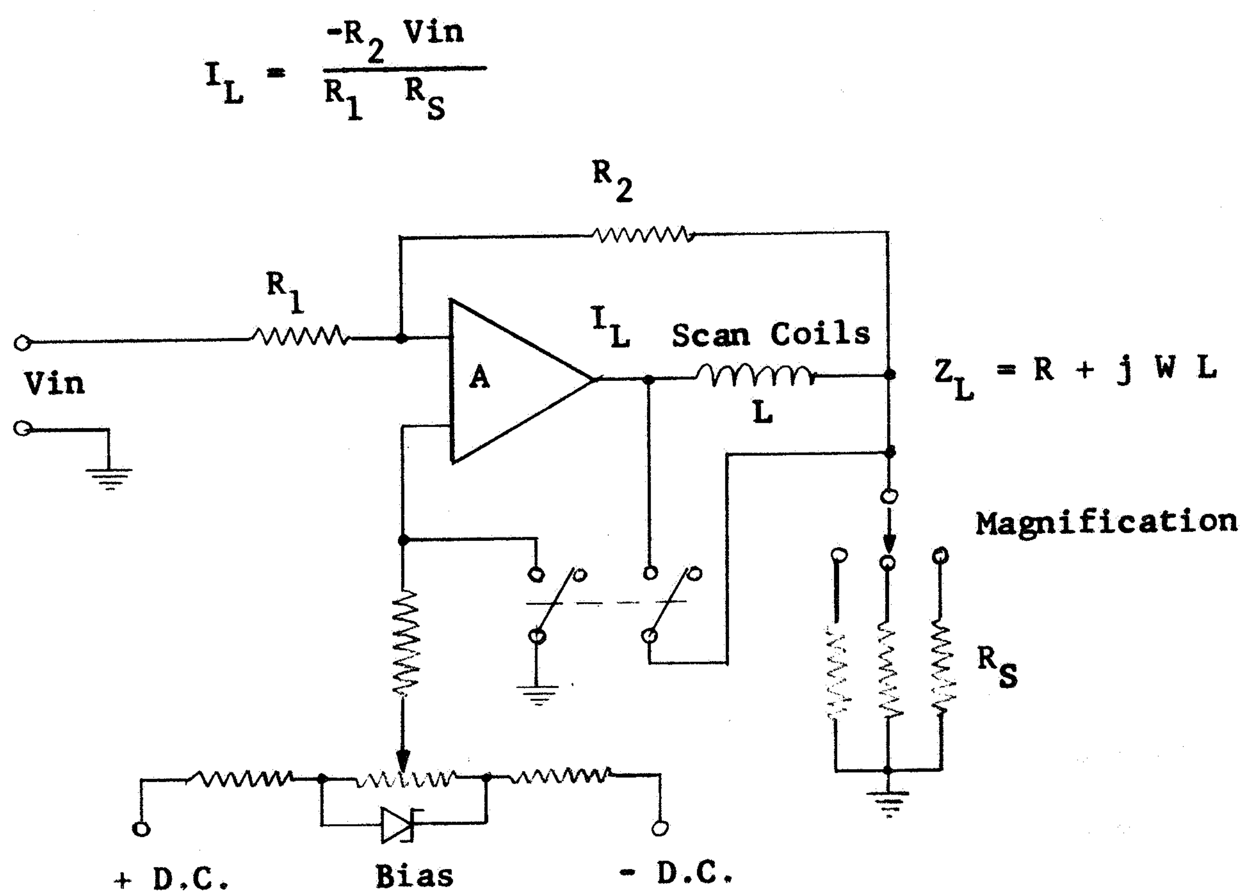


Figure 25 Schematic Diagram - Sweep Current Amplifiers

Table III

Scanning Rates for Sweep Generator of Display System

No. of Scan Lines per Image	Horizontal (X)		Vertical (Y)	
	Sweep Rate	Duration of One Sweep	Sweep Rate	Duration of One Sweep
	500 sweeps/sec	2 m sec	2 sweeps/sec	0.5 sec
250	250	4	1	1.0
	100	10	0.4	2.5
	100	10	12 sweeps/min	5
500	50	20	6	10
	25	40	3	20
	25	40	1.5	40
	12.5	80	0.75	80
1000	6.25	160	0.375	160
	3.125	320	0.187	320
	1.562	640	0.0935	640

Two high speed 2" diameter oil diffusion pumps followed by cryogenic baffles and 2" ball valves provide clean and efficient column evacuation to an ultimate pressure of 10^{-6} to 10^{-7} torr.

The vacuum control will be automatic and shall be housed in front of the column support cabinet. Vacuum cycling signals will be derived from the various vacuum sensing elements. A list of the vacuum system component specifications is given in Table IV.

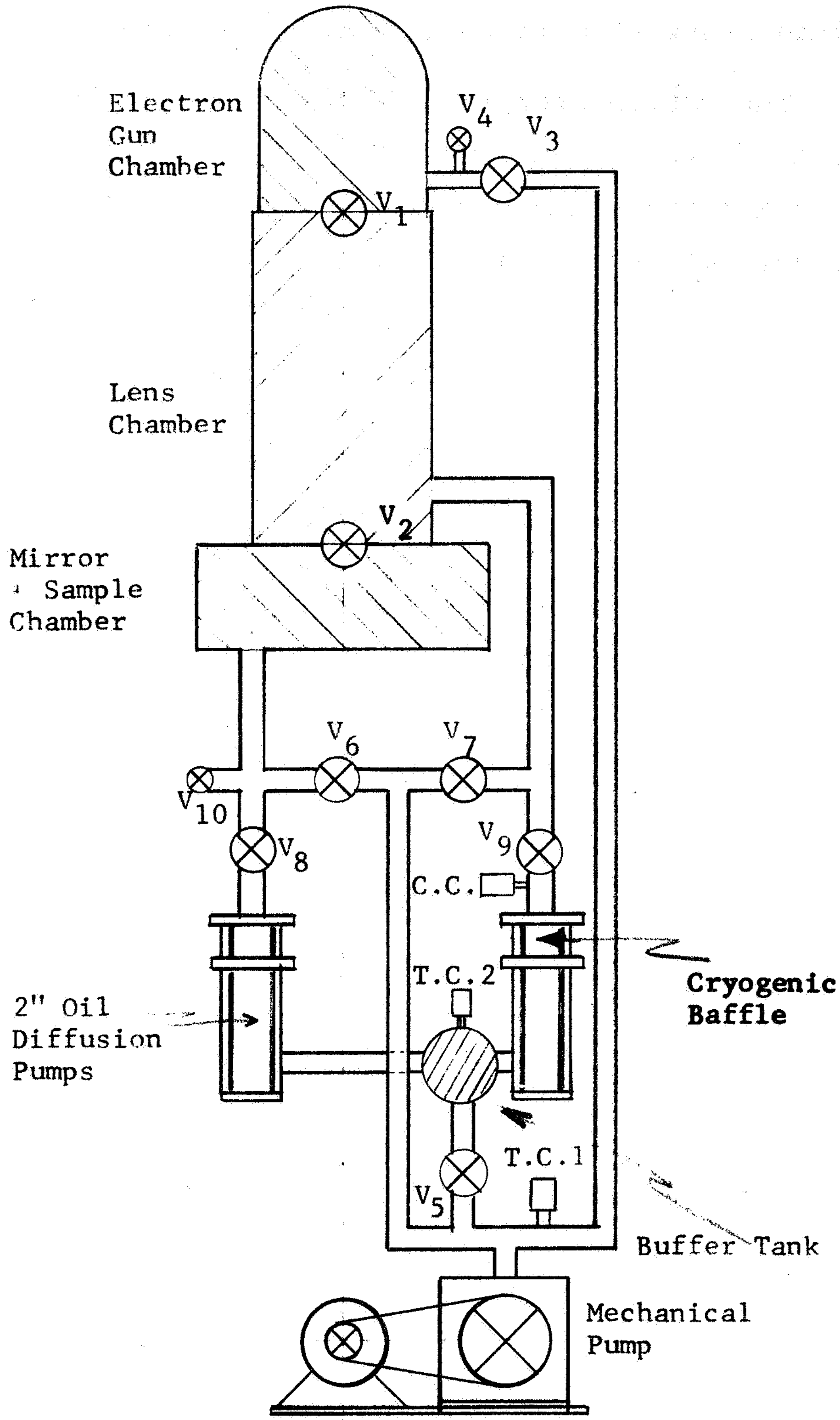


Figure 26 Vacuum System - Schematic Diagram

Table IV

Specifications for Vacuum System Components Shown in Figure 26

Mechanical Pump - 75 liters/min., Precision Scientific No. 79078

Oil Diffusion Pumps (2) - 285 liters/sec., NRC No. HS 2-300

Cryogenic Baffles AMR - Liquid Nitrogen

Buffer Tank, Nicholson Type K-1, 8" dia., 17" long

V_1 and V_2 - 1/2" Port Ball Valve, Hand Operated, AMR No. 10100

V_3 and V_4 - Dual Valve, AMR No. 10201

V_5, V_6, V_7 - 13/16" Port Ball Valve, Motor Activated, A & N No. 1011

V_8, V_9 - 1 1/2" Port Ball Valve, Motor Activated A & N No. 1021

V_{10} - 1/16" Solenoid Valve, Speedivac No. SV1A.

T.C.$_1$ - T.C.$_2$ - Thermocouple Gauge, CVC No. GTC-004

C.C. - Cold Cathode Gauge, NRC No. 851

Appendix A

New Technology

Principles of the Scanning Electron Mirror Microscope

Pages 1-7 of this report review the principles of operation of a new non-destructive instrument to be used for the study of sample topography, surface electric potential, and surface magnetic field distribution. Based on an original concept of Dr. James E. Cline, Electronics Research Center, National Aeronautics and Space Administration, the instrument combines the best features of a scanning electron microscope and an image forming electron mirror microscope. Designed primarily for application to the study of microelectronic devices, the instrument should be widely applicable to the study of metals, ceramics, non-metallics, biological samples, etc.

Design Features

Specific design characteristics which would be related to the efficient and optimum performance of the instrument are given in this report. A tilted electron mirror to allow collection of the primary reflected beam (Pages 6-7), an electron mirror with a multiple electrode configuration to allow control of the axial field gradient at the sample surface, independent of the absolute electron potential (Pages 7-8), an analytical approach to calculation of electron trajectories for the electron mirror (Pages 9-13) and a multiple detector array to allow quantitative analysis and display of surface potential gradients (Page 19).

Demonstration of Feasibility

A prototype instrument was built and used successfully to demonstrate the feasibility of all major aspects of the proposed instrument (Pages 21-43).